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A MODELING PERSPECTIVE FOR
METEOR BURST COMMUNICATION

THESIS

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A MODELING PERSPECTIVE FOR METEOR BURST COMMUNICATION

THESIS

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Preface

The purpose of this thesis is to present a modeling perspective for meteor burst communication. The emphasis is on queueing effects and simulation and not on the detailed characteristics of the meteor burst phenomenon. A short review of meteor burst characteristics and meteor burst communication is provided, however, for a more detailed explanation, the reader is urged to consult the references found in the bibliography. A list of additional references can also be obtained by contacting:

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The results of this research were obtained over a twelve month period and were marked by slow and methodical progress. I am deeply indebted to my thesis advisor, Captain Wade Shaw, for his simulation insights and his resourceful alternatives. A word of thanks is also due to my committee members, Major Thomas Litko and Major John Stibravy, for their assistance in this effort.

Brian C. Healy

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Abstract

Meteor burst communication (MBC) is well suited for military applications. MBC offers better security compared to other long range communication systems because of its low probability of intercept and antijamming characteristics. MBC, however, has two major drawbacks: low throughput and long message waiting time. In order for MBC to be used effectively, methods need to be developed to predict and optimize system performance. The result of this research is the design and development of a methodology to analyze MBC networks.

A decision support system was developed that provides a simulation model for any single or multiple-link MBC network. This model runs on an IBM XT/AT compatible computer and consists of two distinct components. The first component uses engineering parameters to compute intermediate queueing characteristics used by a discrete event simulation component. The simulation component provides point estimates for throughput, message delay, and resource utilization in tabular and graphical form.

The MBC process is shown to be a M/G/1 queue with server vacations. Applicable analytical equations are presented and their limitations are discussed.

Analytical equations and empirical data were both used to validate the MBC performance model.

The modeling perspective presented in this research represents a new and robust method for analyzing MBC networks. Adaptive message routing, flood routing, and priority message traffic are discussed. By separating the engineering parameters of the MBC network from the simulation code, portability, ease of use, and conceptual simplicity was achieved. This research demonstrates the successful marriage of complex communication system engineering with queueing theory and simulation models to produce a highly productive analysis tool.

A MODELING PERSPECTIVE FOR METEOR BURST COMMUNICATION

I. *Introduction*

Background

The earth is constantly bombarded by billions of meteors each day. Most of these meteors burn up when they enter the earth's atmosphere and create meteor trails. These trails usually disappear after a few seconds but last long enough to reflect radio waves. These radio waves are reflected 80 to 120 kilometers above the earth's surface at frequencies ranging from 30 to 120 MHz. Communication systems that use these trails are known as meteor burst networks.

Meteor burst communication (MBC) is well suited for military application. MBC offers better security compared to other long range communication systems. This is due to the low probability of intercept (LPI) and antijamming (AJ) characteristics. MBC is also relatively free from nuclear effects and recovers quickly from High-Altitude ElectroMagnetic Pulses (HEMP). MBC is simple to implement, inexpensive, and highly reliable. Communicating via meteor

trails is passive, renewable, and cost free. MBC hardware is also portable, therefore, ideal for mobile applications.

Because of these advantages, MBC is uniquely suited as a back-up communication system for many C^3I networks. MBC does, however, suffer two major drawbacks: low throughput and long message waiting time. In order for MBC to be utilized effectively, methods need to be developed to optimize the performance.

Simulation is a cost-effective technique which can be used to effectively evaluate MBC networks. Effects on throughput and message waiting time caused by changes in network topology, message transmission protocol, routing algorithms, and variations in network operating parameters can be easily studied with simulation models. Simulation models can be used to develop methods to improve network throughput and message waiting time necessary to make MBC a viable communication medium.

Summary of Past Effort

Two AFIT theses have already been accomplished in the area of MBC simulation. Captain Donald D. Conklin presented a thesis entitled, "Simulation Model of a Meteor Burst Communication System for Data Transmission Protocol Evaluation" in December 1986. His emphasis was on modeling different data transmission protocols for the RADC high-latitude MBC network. He investigated protocol

modifications including message length and structure modifications, overhead reduction, and adaptive message techniques to improve the efficiency of the meteor burst network.

Captain Bruce A. Meyers produced a thesis entitled, "Simulation and Analysis of Networking Techniques in a Multiple Link Meteor Burst Communications Network" in December 1987. His emphasis was on modeling a multiple-link meteor burst network. Meyers designed his model to study MITRE's MBC network. The network consisted of transmitter/receiver nodes at Vint Hill Farms, Virginia; Stockbridge, New York; Bedford, Massachusetts; Loring AFB, Maine; and Omaha, Nebraska. He attempted to investigate the effects of static, flood, and adaptive routing algorithms on the network. He also attempted to simulate a priority traffic queuing system to increase the efficiency of the network.

Both of these theses were designed to study specific MBC networks. Although both are useful for their designed purpose, they have limited use in the study of MBC networks in general. What is needed is a MBC model which can be used to study any single or multiple-link MBC network.

Problem

The problem addressed in this thesis was to develop a model that can be used to relate engineering design specifications to any single or multiple-link MBC network. The model will be designed to run on an IBM XT/AT compatible personal computer by keeping the model conceptually and computationally simple without unnecessary loss of accuracy. This approach provides MBC network designers with a modeling tool which maximizes usefulness and flexibility.

Approach

To solve this problem, a MBC computer model was designed that consists of modules written in Borland's Turbo Pascal version 4.0 and the student PC version of the SLAM II simulation language. This approach exploits the strengths and the weaknesses of each language. Turbo Pascal is designed for scientific applications and has useful screen and file manipulation capabilities. SLAM II is used because of its powerful simulation capabilities.

This computer model consists of a Pascal front-end module, a SLAM II single-link module, and several SLAM II network model examples. The Pascal front-end module uses analytical equations for network specific engineering parameters to generate values for the SLAM II single-link module. The Pascal module generates values of meteor trail interarrival rate, meteor trail duration, and message

duration required by the SLAM II single-link module. The SLAM II single-link module then provides values of average message buffer size, message buffer delay, message waiting time, message transmission time, the number of meteor trails required per message, and throughput.

Each transmitter/receiver pair in the SLAM II network model is a replication of the SLAM II single-link module. The network queueing effects are modeled by the SLAM II simulation language. A 3-node relay network, a 5-node ring network, a 5-node star network, and a 7-node hybrid network model are simulated.

Scope

This thesis effort is designed as a modeling perspective for MBC. The emphasis is on high-level methods to model any MBC network. Detailed analysis for particular networks is not provided. Code is provided for the SLAM II single-link module as well as the 7-node hybrid network model in an effort to explain modeling techniques that a MBC network designer can use to create a particular network.

Assumptions

The following general assumptions are made in this thesis project.

1. Closed form solutions for message throughput and delay only exist for simple message transmission protocols. Closed form solutions are complex, and simulation can be used to generate throughput and delay values.
2. An optimal network topology usually can not be determined. Heuristics may be used to approximate a suitable topology given desired values for throughput and delay.
3. Optimizing both throughput and delay is not possible. Throughput and delay are inversely related. Desired throughput at acceptable delay is determined by the network designer.
4. The SLAM II simulation language will accurately simulate a given set of actual conditions.

The modeling examples provided make the additional assumptions:

- fixed length messages,
- two message transmission protocols,
- constant transmitter bit rates,
- exponential meteor trail arrivals,
- exponential meteor trail durations,
- poisson message arrivals,
- static message routing,
- no message retransmissions,
- no message transmission errors,
- middle-latitude networks,
- normal environmental and propagational effects,

- half-duplex transmission links,
- no priority classes between messages, and
- underdense meteor trails (electron density < 2×10^{14} electrons/meter).

These assumptions, however, are not a limitation. They were selected to keep the models as simple and generic as possible. Whenever possible, methods are discussed to make the models more detailed and user specific.

Standards

The validity of the analytical equations used in the Pascal front-end module is not addressed in this thesis. However, the results of the Pascal front-end module are compared to empirical data. The values of throughput and message delay generated by the SLAM II single-link module are compared to predictions made by existing mathematical formulas. After verification of the SLAM II single-link module, the validity of the SLAM II network model is established.

Objectives

The ultimate objective of this thesis effort is a computer model designed to run on a personal computer. This model is intended to be generic enough to be used for any MBC network yet sophisticated enough to model any degree of detail required by the network designer. To accomplish this ultimate objective, several intermediate objectives are satisfied. These objectives are summarized in Table 1.1.

Table 1.1. Thesis Objectives

NUMBER	OBJECTIVE
1.	Design a Turbo Pascal module to calculate necessary meteor burst parameters for the SLAM II single-link module
2.	Construct a SLAM II single-link module
3.	Use the SLAM II single-link module to simulate two message protocols
4.	Validate the SLAM II single-link module using existing mathematical formulas for throughput and message delay for the two message protocols
5.	Demonstrate how the SLAM II single-link module can be modified to simulate overdense meteor trails
6.	Use the SLAM II single-link module to develop a SLAM II network model
7.	Demonstrate the use of the SLAM II network technique by simulating: -- a 3-node relay network -- a 5-node ring network -- a 5-node star network -- a 7-node hybrid network
8.	Demonstrate the importance of network topology by showing how transmitter relays can decrease message waiting time
9.	Using the SLAM II network model, demonstrate the use of message routing tables to implement static routing
10.	Discuss how static routing tables can be modified to implement adaptive routing
11.	Discuss how flood routing can be implemented
12.	Discuss how priority message traffic can be implemented

Overview of Remaining Chapters

Chapter II is a review of basic meteor trail phenomenology. Chapter III provides a description of meteor burst networks. This chapter compares MBC with other Beyond Line of Sight (BLOS) transmission media and describes advantages and disadvantages of MBC. Chapter IV describes other existing MBC models. Advantages and disadvantages of each model are discussed. Chapter V is a description of the MBC model developed in this thesis effort. Chapter VI is a discussion of the MBC model results. Chapter VII presents thesis conclusions and recommendations for further research.

Appendix A contains a glossary of terms used throughout the thesis. Appendix B describes the significant equations used to generate meteor burst parameters for the SLAM II simulation module. Appendix C is an analysis of MBC performance as a function of important engineering parameters. Appendix D is a user's manual which describes the MBC model software. Appendix E provides the source code for the SLAM II single-link module. Appendix F contains the source code for the SLAM II 7-node hybrid network model. Appendix G contains run time results from the Turbo Pascal front-end module. Appendix H contains the run time results for the SLAM II 7-node hybrid network. Appendix I is a list of MBC consultants who helped in this thesis effort.

II. *Meteor Trail Phenomenon*

Introduction

George Sugar's work in the field of MBC forms the foundation for today's research. His article, "Propagation Via Meteor Trails" published in 1964, provides an excellent overview of meteor burst theory [Sug64]. He describes meteoric particles, meteor trail parameters, overdense and underdense meteor trails, and variations in meteor arrival rate. S. J. Morin from MITRE Corporation describes ionospheric scattering effects on MBC in the report, *Meteor Burst Communications for Military Applications* [Mor85].

Meteoric Particles

Only meteors that burn up in the atmosphere are useful for MBC. Micrometeors are so small that they "float" and do not burn up to produce ionized trails. Large meteors which strike the Earth are too rare to be practical for communication. Meteors that are used for communication can be classified as either shower meteors or sporadic meteors.

Shower meteors are groups of particles that move together at the same velocity and enter the atmosphere at the same time each year. Sporadic meteors, on the other hand, do not move together and appear randomly. The shower meteors are not as common as the sporadic meteors and,

therefore, not as useful. The sporadic meteors make up the majority of the ionized trails used for meteor burst systems.

The mass of sporadic meteors range from 10^{-8} to 10^{4} grams, and the velocities range from 11.3 to 72 km/sec [Man54]. Sugar's research indicates that shower meteors have a similar mass range, although large meteors occur more frequently than smaller meteors. Table 2.1 lists the major meteor showers. The relative intensity is a ratio of the number of shower meteors compared to the number of daily sporadic meteors. The number of sporadic meteors is inversely proportional to their masses [Esh53]. This relationship is illustrated in Table 2.2.

Table 2.1. The Major Meteor Showers [BrS86]

SHOWER	DATE OF MAX	DURATION (DAYS)	RELATIVE INTENSITY
Quarantids	Jan 03	5.0	2.1
Lyrids	Apr 21	8.0	0.9
Eta-Aquarids	May 05	20.0	5.1
O-Cetids	May 19	10.0	6.5
Arietids and Z-Perseids	Jun 05	16.0	11.3
Saggitarids and Capricornids	Jun 12	60.0	2.4
Beta-Taurids	Jun 30	12.0	2.7
Delta-Aquarids	Jul 28	21.0	7.9
Pisces Australids	Aug 03	35.0	3.4
Perseids	Aug 12	15.0	2.1
Orionids	Oct 21	10.0	1.8
Leonids	Nov 17	5.0	0.5
Geminids	Dec 13	3.0	5.8
Puppids	Dec 14	23.0	1.1
Velids	Dec 20	30.0	1.1

Meteor Trail Parameters

Meteor trails are formed when meteoric particles collide with air molecules in the atmosphere. These collisions produce heat, light, and ionization streams. The collision with air molecules causing ionization does not occur until about 120 km from Earth. Ionization is complete about 80 km from Earth at which point the meteors are completely vaporized.

The lengths of the trails are a function of mass and the angle at which the meteors enter the atmosphere. These meteor trails range from 15 to 50 km and have a radius of 0.55 to 4.35 meters. The radius of the meteor trail is a function of altitude and has a mean value of 0.65 meters [BrW78].

The time it takes for the meteor trail to dissipate is a function of meteor size and atmospheric wind [Man54]. Most of the trails that are detected are from small particles which cause trails that last only tenths of a second. Larger particles can cause trails that last for minutes or longer.

Underdense and Overdense Meteor Trails

Meteor trails are classified as underdense or overdense. The difference between these two types of trails is based on electron density. Meteor trails with more than $2x10^{14}$ electrons/meter are considered overdense [Mil87].

Trails with less electrons/meter are called underdense [Mil87]. Table 2.2 compares the differences between overdense and underdense trails.

Overdense trails prevent the penetration of radio waves and cause them to reflect [Mil87]. Underdense trails allow penetration and cause independent scattering of radio waves [Mil87]. As a result, the signals reflected from overdense trails last longer than the signals scattered by underdense trails. Although overdense trails are more effective for MBC, they are not as common as underdense trails and, therefore, are less reliable for communication [Ric82]. The number of overdense trails compared to underdense trails is illustrated in Table 2.2.

Table 2.2. Overdense and Underdense Meteor Size Distribution [Mor85:9]

Mass (grams)	Radius (cm)	Number Swept up by the Earth per Day	Electron Line Density (electrons/meter)
OVERDENSE TRAILS			
10^3	4.0	10^2	10^{20}
10^2	2.0	10^3	10^{19}
10	0.8	10^4	10^{18}
1	0.4	10^5	10^{17}
10^{-1}	0.2	10^6	10^{16}
10^{-2}	0.08	10^7	10^{15}
UNDERDENSE TRAILS			
10^{-3}	0.04	10^8	10^{14}
10^{-4}	0.02	10^9	10^{13}
10^{-5}	0.008	10^{10}	10^{12}

Meteor Arrival Rate Variations

The occurrence of sporadic meteors is determined by several factors. The variation in meteor arrival rate is influenced by diurnal, monthly, and geographic dependencies.

Diurnal Variation. The number of sporadic meteors is influenced most by diurnal variations. This variation is shown in Figure 2.1. In the morning, meteors are encountered by the forward motion of the Earth; but at night, only meteors overtaking the Earth enter the

atmosphere. Because of diurnal variation, the maximum meteor rate occurs around 0400 and a minimum rate occurs around 1800.

Monthly Variation. The concentrations of meteor orbits around the Earth's ecliptic plane cause more sporadic meteors to occur in the summer than in the winter. The tilt of the Earth's axis also contributes to this effect. In the northern hemisphere, maximum meteor activity occurs in July, and minimum activity occurs in February. This variation is illustrated in Figure 2.2.

Geographic Variation. Latitude also affects the number of sporadic meteors. Polar Cap Absorption (PCA) is the result of low-energy cosmic rays caused by solar flares [Ost85]. Because of PCA, the number of useful meteor trails is diminished. This phenomenon is most pronounced at latitudes greater than 64 degrees [Ost85].

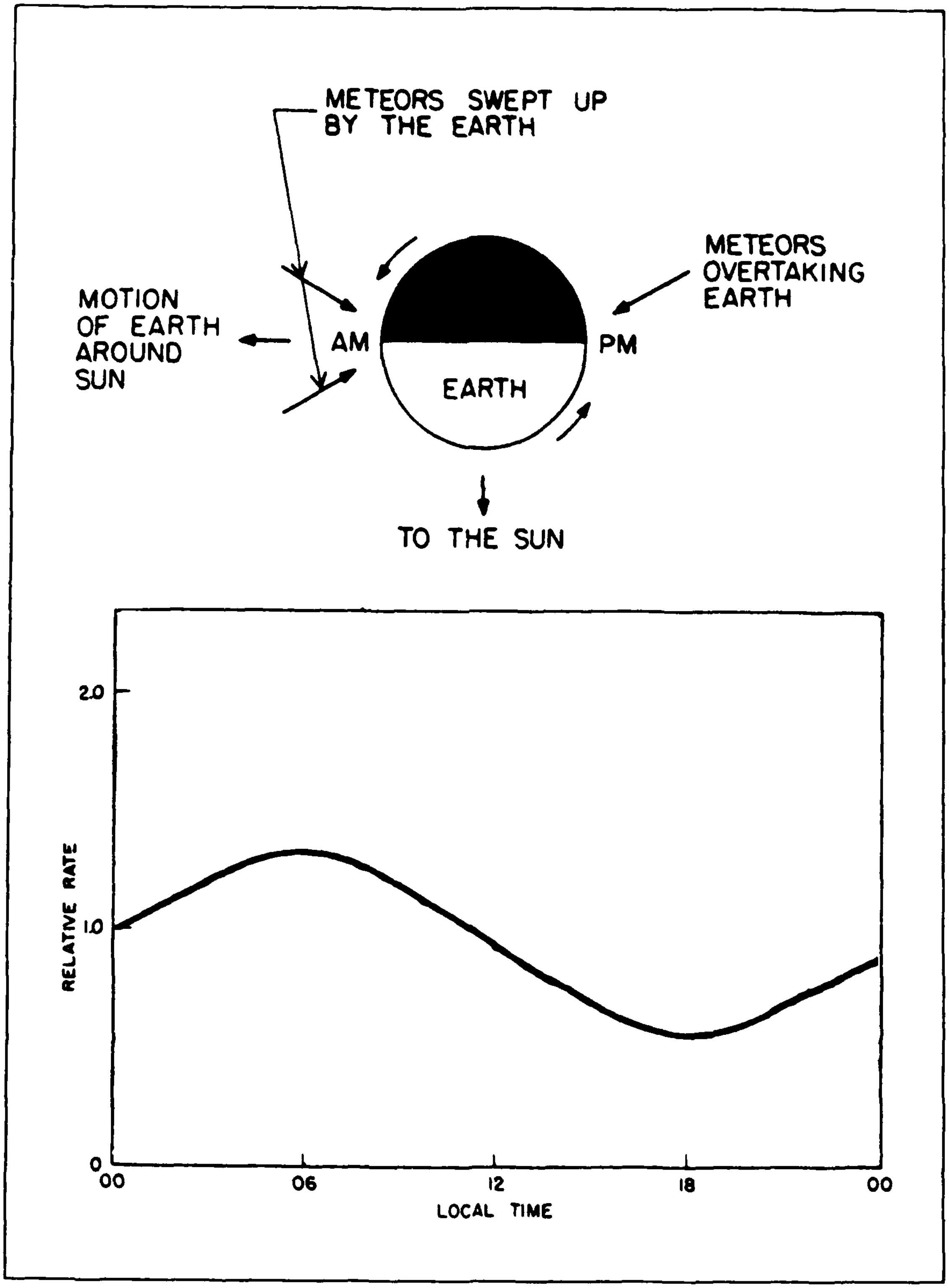


Figure 2.1. Diurnal Variation Phenomena and Daily Variations [Mor85]

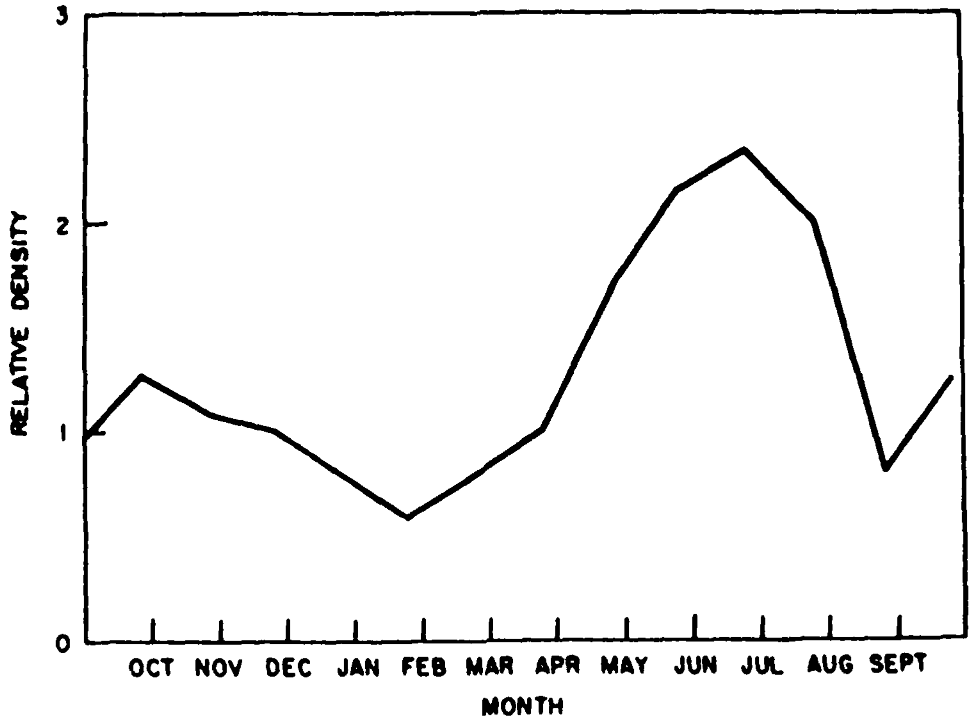


Figure 2.2. Monthly Variation of Meteor Trail Activity [Sug64]

Ionospheric Scattering

Some types of ionospheric disturbances can reflect the VHF radio waves used by MBC. These disturbances take place in the D, E, and F regions of the ionosphere. These regions are illustrated in Figure 2.3. Ionospheric disturbances may reduce or enhance MBC effectiveness.

D Region Disturbances. The D region of the ionosphere extends from 60 to 90 km above the Earth. Wind turbulence in this region can affect the electron density of a meteor trail. This disturbance only has a minor effect on MBC and has no effect at transmitter frequencies above 60 MHz.

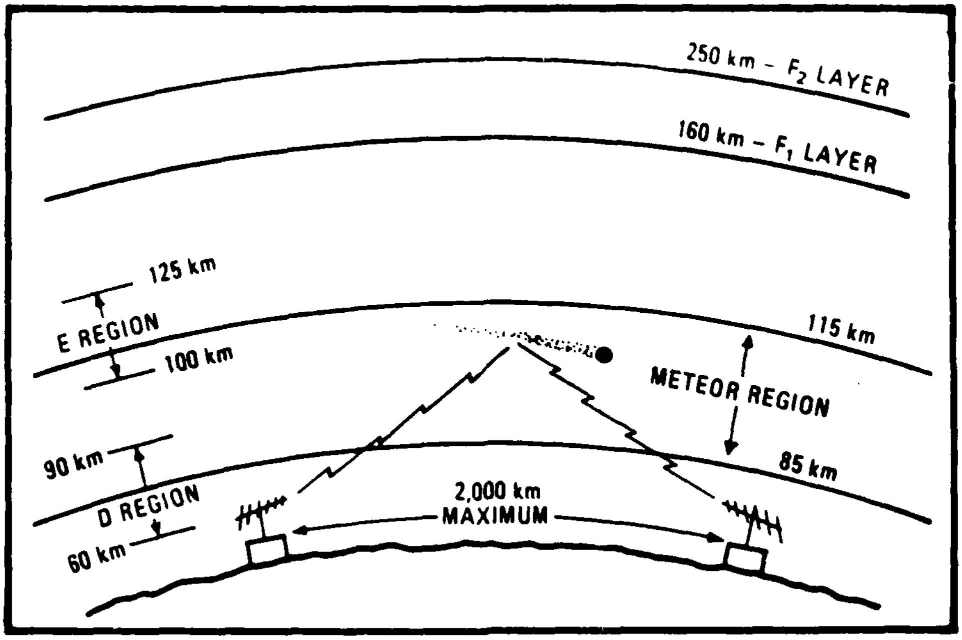


Figure 2.3. Meteor Burst Geometry [Day82]

Sporadic E. Sporadic E is an ionospheric disturbance which occurs within the E region of the ionosphere. This disturbance occurs primarily in the summer at altitudes 90 to 120 km above the Earth. Sporadic E causes continuous reflection of VHF radio waves. This disturbance greatly enhances the effectiveness of MBC, but it reduces the AJ and LPI characteristics inherent to MBC [Ost85].

Spread F. Spread F disturbances occur in the F region of the ionosphere at an altitude range of 150 to 250 km. Spread F is produced by sunspot activity and causes VHF radio waves to be reflected at ranges greater than 4000 km. This disturbance interferes with the reflection of VHF radio waves from meteor trails for transmitter frequencies less than 50 MHz.

Auroral Scatter. Auroral Scatter affects the reflection of VHF radio waves at altitudes from 75 to 135 km. This disturbance forces transmitter bit rates to be significantly reduced to maintain MBC.

III. *Meteor Burst Communication Networks*

Introduction

General Robert T. Herres, former commander in chief of NORAD, stated:

> To respond to the increased Soviet space and air threat, NORAD must be capable of providing timely, reliable, and unambiguous warning and high-confidence assessment for posturing U.S. and Canadian forces for survivability [McJ86:84].

Jam-resistant, survivable, and electromagnetic-pulse (EMP) protected communications are needed in order to accomplish this mission. The NORAD Attack Warning and Attack Assessment (AW/AA) network requires survivable communications. The Air Force is currently developing several systems to meet this communication requirement. The current systems include MILSTAR, Jam-Resistant Secure Communications (JRSC) program, the Groundwave Emergency Network (GWEN), the National Emergency Telecommunications System (NETS), long-haul HF communications, and Meteor Burst Communication (MBC).

The principle of MBC is not new. In fact, this form of communication has been studied for the last 30 to 40 years. MBC, however, has recently become popular because of its antijamming (AJ) features and its low probability of interception (LPI). The advances in microcomputer

technology and inexpensive solid-state memories are also responsible for making MBC desirable [Oet79]. The microcomputer revolution has made it possible to provide the inexpensive transmitters necessary to use the short meteor trail lifetime for communication [KoR86].

MBC is simple to implement, inexpensive, and highly reliable. In addition, MBC has a range from about 400 km to 2000 km [KoR86]. The nuclear survivability is superior to other beyond line-of-sight (BLOS) transmission media such as satellite and HF radio [Oet79]. Several significant meteor burst networks have been in development since the 1950s.

History

Kenneth J. Kokjer presents a description of the first two meteor burst networks that laid the framework for current MBC. The Canadian JANET system was developed in the 1950s for teletype communications between Toronto and Port Arthur [KoR86]. It is the forerunner of current meteor burst networks. The JANET system used full duplex transmission with VHF frequency of 50 MHz and duty cycles around 0.1 [KoR86].

The COMET system was a meteor burst network established between the Netherlands and Southern France during the 1960s and 1970s [KoR86]. Worst case message delays for the COMET system were 3 to 4 minutes [KoR86].

Current Meteor Burst Communication Networks

Three current MBC networks include the RADC test link, SNOTEL (SNOw TELemetry), and the Alaska Meteor Burst Communications System (AMBCS). The RADC test link is composed of a transmitter located at Sondrestrom Air Base and a receiver located at Thule Air Base in northern Greenland. This test link is designed to study the effects of high-latitude on MBC.

SNOTEL is operated by the U.S. Department of Agriculture and is currently the largest meteor burst network in active use [Con86]. The SNOTEL system contains over 500 remote sites located in 11 western states [Day82]. These sites are used to transmit data on snow cover, temperature, and precipitation [Day82].

AMBCS is operated by several government bureaus and is located in Anchorage [Day82]. The AMBCS system is used to transmit weather and flight data and teletype messages [Day82].

The U.S. Navy is using MBC networks as part of the Navy Blue Locator program [Con86]. This network is used to relay ship locations for ship-to-ship and ship-to-shore communications [Con86]. The U.S. Air Force Alaskan Air Command is also experimenting with MBC as a back-up for MILSTAR and AFSATCOM satellite systems [Con86]. The Defense Communications Agency is investigating the use of MBC for the Minimum Essential Emergency Communications Network

(MEECN). Other agencies using meteor burst systems include the Department of Energy and the National Oceanic and Atmospheric Administration (NOAA).

Performance Characteristics

MBC links can average 100 words per minute with over 90 percent reliability at ranges up to 2000 km [KoR86]. This communication medium can transmit data at about 2.5 kbps but averages 75 bps due to the low average duty cycle [McJ86]. The maximum distance a transmitter can send is 2000 km. This limitation is a result of the curvature of the Earth and not of the transmission system [Day82]. See Figure 2.3. Greater distances, however, can be achieved by relaying the signal.

In addition to the variations produced by diurnal, monthly, and geographic effects, the number of meteor trails useable for communication is a function of transmitter power, transmitter and receiver antenna gain, transmitter frequency, range, and transmitter bit rate. The effect these parameters have on detected meteor trails is described in Appendix C. The location of "hot spots" between a transmitter and receiver also has a major impact on network performance.

Transmitter Power. Increasing transmitter power increases the length of time a meteor trail can be used for communication. Increasing the transmitter power also allows

smaller meteor trails to be detected [Day82]. Figure C.1 shows the relationship between transmitter power and detected meteor trails.

Antenna Gain. Increasing antenna gain increases the time a meteor trail can be used for communication. However, increasing the gain results in a narrower beamwidth and decreases the common volume of the transmitter and receiver antenna beams [Day82]. Because the antenna covers less area in the sky, fewer meteors can be detected. See Figure 3.1. Most meteor burst networks use antenna gains that range from 10 dBi to 24 dBi [Haa83]. The relationship between transmitter antenna gain and observed meteor trails is illustrated in Figure C.3.

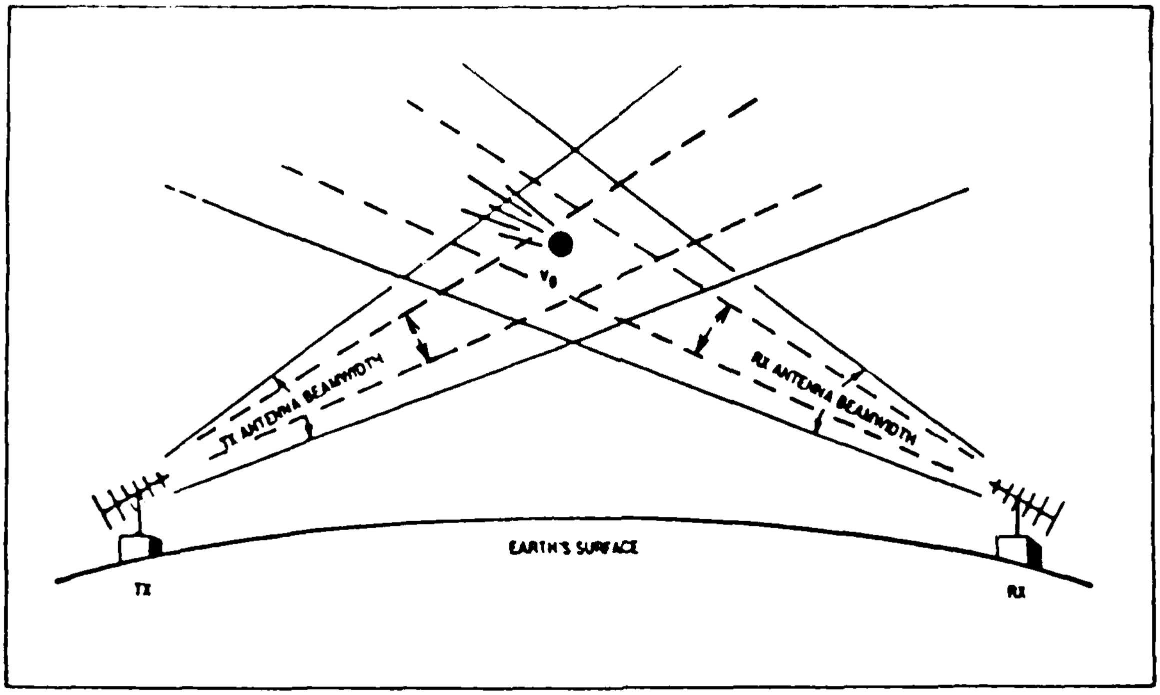


Figure 3.1. Common Volume of the Transmitter and Receiver Antenna Beams [Mor85:32]

Transmitter Frequency. MBC operates at frequencies of 30 to 120 MHz. Frequencies below 30 MHz can not be used because proper ionospheric reflection will not occur [Ric82]. Frequencies above 50 MHz cause longer message waiting times [Ric82].

Higher operating frequencies, however, can offset the effects of PCA at high-latitude. According to J. C. Ostergaard, PCA is inversely proportional to the square of the frequency [Ost85]. Higher frequencies also reduce the effect of wind turbulence, Sporadic E, Spread F, and auroral scatter. For a given level of ionospheric disturbances, there exists an optimal operating frequency.

The effects of frequency on detected meteor trails is illustrated in Figure C.5.

Range. The range between a transmitter and receiver has a pronounced effect on performance. Although ranges between 400 and 2000 km are possible, long message waiting times are experienced near the limits. For a given MBC link, there exists an optimal transmission range. Operational experience indicates an optimal range is around 1000 km. This relationship is shown in Figure C.7.

Transmitter Bit Rate. Higher bit rates permit faster message transmission. However, higher bit rates reduce the length of time a meteor trail can be used for transmission. For a given set of system parameters, there exists an optimal bit rate which will yield maximum throughput. Bit rate effect on detected meteor trails is described in Figure C.9.

Hot Spots. Hot spots are areas of the sky which are most likely to produce meteor bursts useful for communication [Mor85, Ost85, Sug64, HiP56]. Hot spots are the result of geometric factors that determine the reflection path between a transmitter, meteor trail, and receiver [Mor85]. Hot spots lie on either side of the great circle path between a transmitter and receiver [Mor85, Sug64, HiP56]. The location of hot spots, however, is influenced by diurnal variations [Mor85, Sug64]. Using hot spots significantly improves MBC performance.

Transmission Protocols

Transmission protocols are an important consideration for MBC networks. Because of the short meteor trail duration, transmission protocols have to be extremely efficient to maximize throughput performance. Captain Conklin performed a detailed analysis of the Corvus protocol used in the RADC high-latitude test link in his thesis. His objective was to analyze the effect of transmission protocols on system throughput.

This thesis considered two simple protocols. These protocols are referred to as Protocol 1 and Protocol 2 and were used to satisfy objective 3 from Table 1.1. A fixed length message is assumed for both protocols. In Protocol 1, a receiving station continually broadcasts a probe signal. A transmitting station begins transmitting when a probe signal is received. The probe response delay for Protocol 1 is at most equal to the one-way propagation delay between the transmitter and receiver [Mil86, Mil87]. See Figure 3.2.

Protocol 1 is known as message piecing [Haa83]. Every meteor trail long enough to complete the probe response delay and transmit at least part of the message is used [Haa83, Mil86, Mil87].

Protocol 2 is simpler to implement than Protocol 1 and decreases transmission requirements [Mil86, Mil87]. In Protocol 2, a transmitting station broadcasts a probe signal

when it has a message to transmit. A communication link is established when the transmitter receives a response from the desired receiving station. The worst case probe response delay is equal to the two-way propagation delay from the transmitter to the receiver [Mil86, Mil87]. See Figure 3.2.

In this protocol, only meteor trails long enough to complete the probe response delay and deliver the entire message are used for communication [Haa83, Mil86, Mil87]. If a message is not completed before the end of the trail, the entire message must be retransmitted. This protocol is referred to as single burst transfer [Haa83].

Comparison with other Communication Systems

MBC provides an alternative for other long-range communication systems. MBC has many significant advantages over HF radio, microwave, telephone lines, and satellites.

HF Radio. MBC is affected less by ionospheric disturbances including disturbances caused by nuclear explosions than HF radio [Oet79]. HF radio also requires different frequencies for day and night because of changes in the ionosphere [Day82].

Additionally, auroral activity presents less of a problem for MBC than for HF radio [Oet79]. MBC resistance to auroral disturbances is a significant difference in northerly or southerly latitudes where auroral activity is

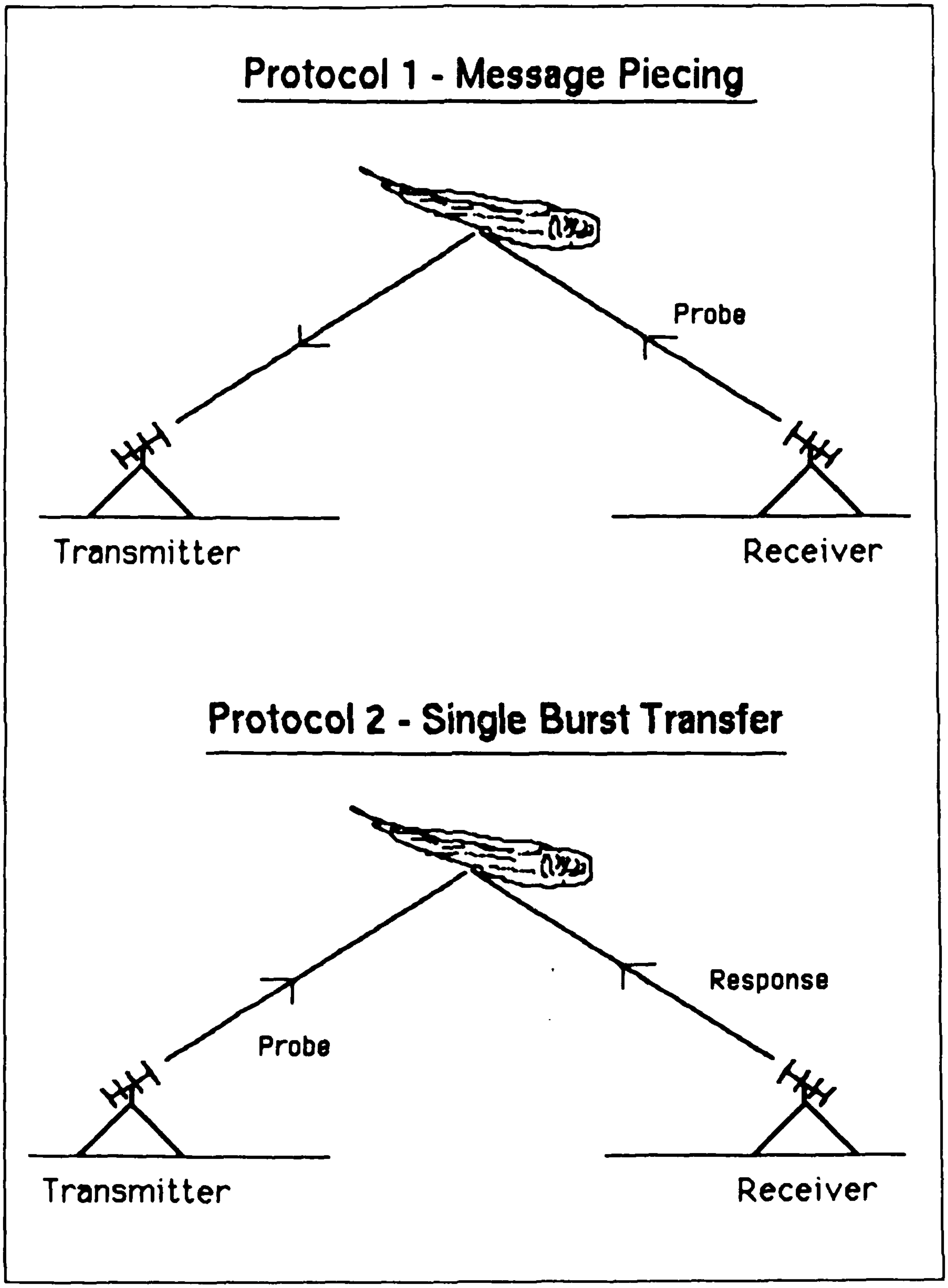


Figure 3.2. Transmission Protocols

the greatest. Auroral disturbances can reduce the reliability of HF radio to 30 percent [KoR86].

MBC requires less complex hardware than HF radio and, as a result, is less expensive to operate. HF radio also suffers from selective fading, skip distances, maximum useable frequency, and problems with determining optimum frequency of transmission [KoR86].

Microwave and Telephone. In contrast with MBC, microwave is a line-of-sight (LOS) transmission medium [KoR86]. This system requires repeaters to obtain long range communication. Telephone lines also require hardware installations to propagate messages. The need for additional hardware increases the cost and limits the flexibility of these alternatives.

Satellite. The closest comparison to MBC is satellite communication. Satellites can provide more efficient message transmission than MBC. However, the cost of the satellite is an important consideration when installing a communication network. Satellites are also more susceptible to interference.

Military Applications

MBC is well suited for military application because of its unique characteristics. MBC offers many advantages over existing long range communication systems. However, there are certain disadvantages which limit the application of

this type of communication. These disadvantages are currently being studied, and improvements are being made.

Advantages. LPI/AJ properties make MBC extremely attractive for military application. These advantages combined with MBC nuclear environment capability makes this form of communication important. MBC is also ideal for portable and mobile applications. Portability makes MBC suitable for disaster and emergency communications.

Security and Interference. MBC offers better security compared to other long range communication systems. This is due to LPI and better resistance to jamming. Meteor burst transmissions are characterized by small footprints due to the nature of the path from a transmitter to a receiver [Ric82]. In order for a meteor burst transmission to be jammed or intercepted, a jammer or interceptor must duplicate the geometry of the transmission or be within the same receiver footprint [KoR86]. This is especially difficult to do for meteor burst signals. Further security can be provided by encrypting messages prior to transmission.

Resistance to Electromagnetic Pulses. MBC is relatively free from nuclear effects and recovers quickly from high-altitude electromagnetic pulses (HEMP) [McJ86]. Because of this advantage, MBC is being investigated as a back-up communication system for many C^3I networks. NORAD is currently considering MBC as a back-up system in the

AW/AA network. During and after a nuclear attack, MBC may be one of the surviving communication channels available.

Disadvantages. Long message delay times and minimum transmission range are two major disadvantages of MBC. Because of the short lifetime of meteor trails, most messages require several trails for transmission. This causes low average bit rate and results in long message delay times.

Improvements. Several alternatives have been suggested to improve the throughput and reduce the delay of MBC. Adaptive information rate modems, changing antenna radiation patterns, increasing transmitter power, frequency diversity, space diversity, and rapid signal acquisition techniques are currently being investigated to improve throughput and delay.

IV. *Existing Meteor Burst Communication Models*

Introduction

Modeling can be a powerful tool for studying existing meteor burst networks and for the design of new networks. Several simulation and analytical models have been developed to study the performance characteristics of MBC. These models were designed to study single MBC links or networks of transmitters and receivers. Most of these models can be classified as either reference models or physical propagation models.

Reference and Physical Propagation Models

Reference models use experimental data from existing meteor burst links to extrapolate performance characteristics for an arbitrary link. The reference model concept is the result of work by Laurence A. Manning [IBM85]. Manning theorized that the meteor arrival rate for an arbitrary link could be determined from a known arrival rate on an existing link. He determined that the unknown arrival rate was proportional to the:

- transmitter power,
- transmitter antenna gain,
- receiver antenna gain,
- receiver detection threshold, and
- frequency

between the arbitrary link and the known link [IBM85, Man54]. This relationship, however, assumes that meteors arrive uniformly over the transmitter/receiver common volume [IBM86]. See Figure 3.1 for an illustration of the transmitter/receiver common volume.

Scale factors are used to compensate for differences between the known link and the arbitrary link. Additional meteor trail properties can be included in the model by adding scale factors. The reference model is conceptually and computationally simple, easy to use, and relatively accurate [IBM85]. The reference model, however, is only as accurate as the scale factors used. As the scale factors become more complex, the reference model becomes less useful [IBM85].

Physical propagation models are based directly on experimental data for meteor orbits and fluctuations [Bro85]. Physical propagation models must include every physical meteor property to accurately simulate the interarrival time and duration of meteor trails [Bro85]. This type of model is more complex than the reference model. However, physical propagation models are more accurate than reference models at extreme values of latitude, frequency, and range [Bro85, Bro86].

Single-Link Models

Single-link models are designed to evaluate the transmission process between a single transmitter and receiver. Single-link models can not evaluate queueing effects and message waiting time results present in a network of transmitters and receivers. Existing single-link models are either physical propagation models or reference models.

CSC Meteor Burst Model. The CSC Meteor Burst Model is an analytical physical propagation model developed by David Brown. Two versions of the CSC model exist. One is designed for a IBM XT/AT compatible PC computer and requires a math coprocessor and 256K of RAM [Bro88]. The other is designed for the VAX 8650 [Bro88]. The model predicts meteor arrival rate, meteor trail duration, duty cycle, and noise level. Hot spot patterns and message delay statistics are optional outputs. An EGA card is required to produce graphics output of hot spot locations on the PC [Bro88].

Brown's model uses physical meteor properties from *Meteor Astronomy* by A. C. Lovell [Bro85, Bro86]. The physical properties which are modeled include:

- meteor orbits around the sun,
- meteor trail decay,
- galactic noise,
- underdense trail specular scattering, and
- radio wave reflection from the ground [Bro86].

The model was originally created to be an antenna system design tool [Bro86]. The model provides antenna

files for Yagi and Dipole antenna patterns [Bro88]. New antenna files can be created by modifying these files. Recent enhancements to the model include:

- shower meteor effects,
- overdense meteor bursts,
- transverse resonance effects,
- trail formation effects,
- stony and icy meteors, and
- airborne terminals, [Bro88].

The current model yields best results for middle-latitudes and frequencies close to 40 MHz [Bro88].

Conklin Model. Captain Conklin's model is a physical propagation model designed specifically to study the RADC high-latitude test link in northern Greenland. This model uses simulation to study the effects of transmission protocols on system throughput.

This is a simplistic physical propagation model. Mean values for meteor trail interarrival time and meteor trail duration for both overdense and underdense trails are measured directly from the physical link [Con86]. Exponential distributions are then applied to these measured mean values to calculate simulation values [Con86]. Overdense trails are simulated by assuming a 4:1 ratio of underdense meteor trails to overdense meteor trails [Con86].

There are two major limitations to this model. The model can only be used for a particular link from which the measured values were taken. In addition, the model is limited to fixed transmitter power, antenna gain,

transmitter frequency, range, and transmitter bit rate for the particular link.

Hampton Model. The Hampton model is an analytical reference model that uses the COMET MBC link as a reference link. This model consists of a set of equations used by Jerry R. Hampton and is not a computer model. Predictions for an arbitrary link are made by relating the transmitter antenna gain, range, receiver antenna gain, transmitter power, and frequency for the arbitrary link to the COMET link [Ham85, Oet79].

The Hampton model predicts the time required to transmit a message to an arbitrary number of receivers using broadcast transmission and a time varying BER [Ham85]. The model uses Automatic-Repeat-Request (ARQ) and Hybrid ARQ/FEC error control [Ham85]. The Hampton model also computes optimal data rate and packet sizes as a function of message size [Ham85].

BLINK Model. The BLINK model is an analytical reference type MBC prediction model. The model is written in Pascal and was designed by Dr. G. A. Marin from IBM [IBM86]. The model was enhanced by Dr. J. A. Weitzen of Signatron Corporation. Dr. Weitzen added overdense meteor trails to the model and scale factors for antenna patterns and for diurnal and monthly variations in meteor arrival rate [IBM86].

The reference equations in BLINK are derived from the paper, "Analysis of Meteor Burst Communications for Navy Strategic Applications" produced by Meteor Communications Corporation (MCC) [IBM86]. This model also relies on the work done by L. A. Manning [Man54] and Haakinson [Haa83].

BLINK calculates UMBPH, AMBPH, throughput, and message delay. UMBPH is the total number of meteor bursts predicted per hour. AMBPH is the number of predicted meteor trails per hour with duration long enough to transmit an entire message. Protocol 2 is used to calculate throughput and message delay.

BLINK is also capable of predicting line-of-sight (LOS) results. VHF troposcatter propagation and LOS/diffraction results are calculated for ranges less than 300 km [IBM86]. Both of these media provide continuous LOS propagation paths [IBM86]. BLINK will determine whether VHF troposcatter, LOS/diffraction, or meteor burst is the predominate transmission medium over a particular link.

Nuclear results can be calculated by BLINK. A program called the Communications Assessment Program (CAP) provides optional nuclear environment input to BLINK [IBM86]. CAP generates values for excess path attenuation between a transmitter and receiver due to D-layer absorption caused by a nuclear detonation [IBM86].

The BLINK model has two significant limitations. The primary limitation is caused by ignoring the effect of

antenna patterns [IBM86]. The effect of antenna patterns has a profound impact on MBC performance. BLINK also does not consider the effect of hot spots on MBC [IBM86].

MITRE Link Model. The MITRE link model is a single-link analytical reference model developed by MITRE Corporation. The MITRE link model is an enhancement of the ITS BURST model without the network modeling capability. The MITRE model added overdense trails, adaptive data rates, and throughput calculations to the ITS BURST model [Hir85].

Network Models

The network models calculate queueing effects and network waiting time results for multiple transmitters and receivers. Except for the ITS BURST model, values for meteor trail arrival rate per link are input to the network models. BURST calculates both meteor trail arrival rate per link and network waiting times. Except for the BURST model, queueing effects and network waiting time results are calculated with the use of simulation.

ITS BURST Model. The ITS BURST model is a network reference model developed by the Institute for Telecommunications Sciences (ITS). The model is written in Fortran and runs on an HP 1000 operated by ITS. Users can access the model via modem.

BURST predicts message waiting time as a function of frequency, transmitter and receiver characteristics, range,

diurnal and seasonal effects, and transmission protocol [Haa83]. BURST can model networks with up to four nodes. BURST uses Protocol 1 or Protocol 2 for message transmission. The reference equations in BURST are derived from the MCC document, "Analysis of Meteor Burst Communications for Navy Strategic Applications."

The message waiting time calculated by BURST is the time to completely transmit a message with probability supplied by the user. The message waiting time includes the queueing effects present in the network.

BURST also has the option of providing directional antennas. Three patterns are available: 1) Omnidirectional, 2) Dipole, and 3) Hunchback [Haa83].

The BURST model has three limitations. It is limited to underdense trail predictions, fixed data rates, and networks with a maximum of four nodes [Hir85].

RESQ Model. The RESQ model is a research queueing package developed by IBM. The RESQ model can calculate throughput and delay values for up to 30 node networks [IBM85]. RESQ measures means, standard deviations, and statistical distributions for throughput, utilization, delay, and message buffer space [IBM85].

MITRE Network Model. The MITRE network model was developed in Pascal by MITRE Corporation. The MITRE network model can simulate MBC networks with up to 50 nodes [Hir85].

This model automatically uses flood routing for message transmission.

Inputs to the model include the number of nodes in the network, the maximum number of hops per message, and the predicted number of meteor trails per link [Hir85]. Output consists of the cumulative distribution of waiting time for all paths which are less than the maximum number of hops [Hir85]. A summary of flood routing waiting times at 50 and 90 percent confidence levels is also output by the model [Hir85].

Summary of Meteor Burst Communication Models

All of the meteor burst models are summarized in Table 4.1. Max nodes refers to the maximum number of nodes in the network. Single-link models have a maximum of two nodes. MITRE link refers to the MITRE link model, and MITRE ntwk refers to the MITRE network model. The Hampton model is not a computer model; therefore, it has no computer requirements.

The BLINK model was chosen as a baseline for a new model called BLINK2. BLINK2 is used in the modeling perspective described in Chapter V.

Table 4.1. Summary of Meteor Burst Communication Models

SIMULATION MODEL	PREDICTION TECHNIQUE	MAX NODES	PROGRAM LANGUAGE	COMPUTER REQUIREMENT
SINGLE-LINK MODELS				
CSC	physical	2	Fortran	PC & VAX 8650
Conklin	physical	2	Pascal	VAX 11/785
Hampton	reference	N/A	N/A	N/A
BLINK	reference	2	Pascal PL/1	PC IBM 4341
MITRE link	reference	2	Fortran	VAX 11/780
NETWORK MODELS				
BURST	reference	4	Fortran	HP 1000
RESQ	N/A	30	PL/1	IBM 4341
MITRE ntwk	N/A	50	Pascal	VAX 11/780

V. *Modeling Perspective*

Introduction

The major objective of this thesis effort is to design a model to predict MBC performance. This chapter describes a perspective used to create a computer model to satisfy this objective. This computer model was designed for portability, ease of use, and conceptual simplicity to provide maximum usefulness to the network designer.

Portability is ensured by designing the model to run on an IBM XT/AT compatible personal computer. Ease of use is provided by a user-friendly interface. Conceptual simplicity is provided by the modular design of the model.

The model consists of several sub-modules and two main modules. The sub-modules are designed to provide an interface between the two main modules and the user. A description of the sub-modules is provided in Appendix D. The first main module is a revision of the BLINK model written in Pascal. This revision is called BLINK2. BLINK2 is designed to provide values of meteor trail interarrival time, meteor trail duration, and message duration to be used by the second main module. The second main module is written in the SLAM II simulation language [Pri86]. This module simulates a single MBC link. Conceptual simplicity is achieved by decoupling the engineering parameters from

the queueing module. For network simulation, the single-link module is replicated for each node in the network. This modeling perspective is described in Figure 5.1.

M/G/1 Queue with Server Vacations

The Meteor Burst Communication process can be visualized as a M/G/1 queue with server vacations. A M/G/1 queue has exponentially distributed interarrival times, a general service time distribution, and one server. Server vacations refer to the process of a disappearing server at a random time for a random duration.

Messages are assumed to arrive randomly (exponential interarrival time) to a transmitter. The server in the MBC scenario is the meteor trail used for transmission. The service time is a function of meteor mass, trail altitude, message size, transmission protocol, and engineering parameters. The service time is assumed to have a general distribution. The meteor trail duration is greater than or equal to the service time and is assumed to have an exponential distribution [Sug64, Oet79, Ost85, Mil87].

Server vacations are caused when the received signal level (RSL) falls below the receiver threshold as the meteor trail diffuses. The time between server busy periods is derived from the meteor trail interarrival time and is determined by diurnal, seasonal, and geographic variables as well as the engineering parameters that characterize the MBC

link. The meteor trail interarrival time is assumed to have an exponential duration [Sug64, Oet79, Ost85, Mil87]. The service rate is determined by the transmitter bit rate and message protocol used.

Some analytical results exist for the M/G/1 queue with server vacations. The current state of the art is summarized in articles written by Fuhrmann and Cooper [FuC85], Keilson and Servi [KeS87], Harris and Marchal [HaM88], and Shanthikumar [Sha88]. Adapting their results to the MBC scenario, expressions for the number of messages in a transmitter buffer, meteor trail duration, meteor trail interarrival time, and message waiting time can be derived.

The number of customers in a M/G/1 queue (i.e. the number of messages in a transmitter buffer) with generalized server vacations was shown by Fuhrmann and Cooper to be the convolution of two probability generating functions (pgf). The first pgf is for the number of customers in a M/G/1 queue without server vacations. The second pgf is for the number of arrivals during the residual of a vacation period [Sha88, HaM88].

Analysis performed by Keilson [Kei63] contain results for preemptive resume and preemptive repeat M/G/1 vacation queues. These results were derived assuming Poisson arrivals and first-in-first-out (FIFO) queueing discipline. However, for this analysis, these results are limited to expressions for service time distribution.

The pgf for the number of customers in a M/G/1 queue with server vacations is given by Harris and Marchal:

$$\pi(z) := \frac{K(z)\cdot(z-1)\cdot(1-\rho)}{z - C(z)\cdot K(z)} \cdot \frac{1 - C(z)}{\lambda\cdot v\cdot(1-z)} \qquad (1)$$

where:
- λ --> customer arrival rate
- $K(z)$ --> pgf for the number of arrivals during a service period
- $C(z)$ --> pgf for the number of arrivals during a vacation period
- v --> mean length of a vacation [HaM88]

This pgf is the result of the convolution of the two pgfs described by Fuhrmann and Cooper.

Keilson and Servi derived expressions for the busy period density for service time, vacation durations, and waiting time. Their results are in the form of Laplace transforms.

The Laplace transform for the busy period density for service time is:

$$\alpha_B(s) := \alpha_T\left[s + \lambda - \lambda \cdot \alpha_B(s)\right] \qquad (2)$$

where:

α_T --> Laplace transform for service time for a M/G/1 queue with server vacations (See Keilson [Kei63] for analysis)

λ --> customer arrival rate [KeS87]

The Laplace transform for vacation durations was derived to be:

$$V(\omega) := \omega + \lambda \cdot \alpha_T(\omega) - \lambda \qquad (3)$$

where:

λ --> customer arrival rate

$\alpha_T(\omega)$ --> Laplace transform for service time [KeS87]

The Laplace transform for waiting time was derived to be:

$$w(s) := s + \lambda - \lambda \cdot \alpha_B(s) \qquad (4)$$

where:

λ --> customer arrival rate

$\alpha_B(s)$ --> Laplace transform for busy period density for service time [KeS87]

These results can be used to calculate meteor trail duration, meteor trail interarrival time, and message waiting time. However, these results are based on the following assumptions:

1) Poisson arrivals,
2) infinite queueing capacity,
3) first-in-first-out (FIFO) service discipline,
4) server vacations independent of customer arrivals, and
5) nonpreemptive service [Sha88].

Assumptions 1, 3, and 4 are compatible with the MBC scenario. However, assumptions 2 and 5 are violated. Assumption 2 is not as significant as assumption 5. Message buffers could be simulated as infinite queues provided the system was ergodic. However, the server (i.e. the meteor trail) can clearly preempt the transmission of a message when it disappears. Although Fuhrmann and Cooper propose that preemptive service can be modeled as nonpreemptive by using appropriately longer service times.

Results for Protocol 2 delay are described in [IBM86]. These results use the Pollaczek-Khinchin equation for waiting time assuming a M/G/1 queue without server vacations. An effective service rate is determined from obtaining moments of the distribution for message transmission time. These results include the following equations:

The distribution for message transmission time is:

$$B(t) := P(T \le t) \quad = 1 - e^{-AMBPM\cdot\left[t-t_{d}\right]} \qquad \text{if} \quad t > t_{d} \tag{5}$$

where:

B(t) --> distribution for message transmission time

AMBPM --> the number of meteor trails long enough to completely transmit a message

t_d --> message duration

The Laplace transform of B(t) is:

$$\beta(s) := \frac{e^{-s\cdot t_{d}}\cdot AMBPM}{s + AMBPM} \tag{6}$$

Moments of T are obtained from $\beta(s)$:

$$T^{k} := (-1)^{k}\cdot\frac{d^{k}}{ds^{k}}\cdot\beta(s) \tag{7}$$

The mean transmission time is:

$$T := \frac{1 + t_{d}\cdot AMBPM}{AMBPM} \tag{8}$$

The second moment of T is:

$$T^{2} := \frac{\left[t_{d}\right]^{2}\cdot AMBPM^{2} + 2\cdot\left[t_{d}\right]\cdot AMBPM + 2}{AMBPM^{2}} \tag{9}$$

Message delay was derived to be:

$$w := \frac{\mu \cdot T^2}{2 \cdot (1 - \rho)} \qquad (10)$$

where:

w --> queueing delay

μ --> message arrival rate

AMBPM --> number of meteor trails long enough to completely transmit a message

ρ --> μ/AMBPM

The analytical results become much more complex when additional assumptions are made. If arrivals are not Poisson (i.e. general, Gamma, or deterministic distributions), if multiple servers are present (i.e. using multiple meteor bursts), or priority service disciplines are used than results are not easy to derive analytically.

These modifications, however, can easily be simulated. Once a simulation model is created and validated, modeling any modification to the system is much simpler. Simulation can also be used to gain insight to the problem and help extend the analytical results.

BLINK2 Single-Link Module

The BLINK model developed by IBM was used as a baseline for BLINK2. BLINK2 is the result of numerous modifications and additional calculations. BLINK2 is

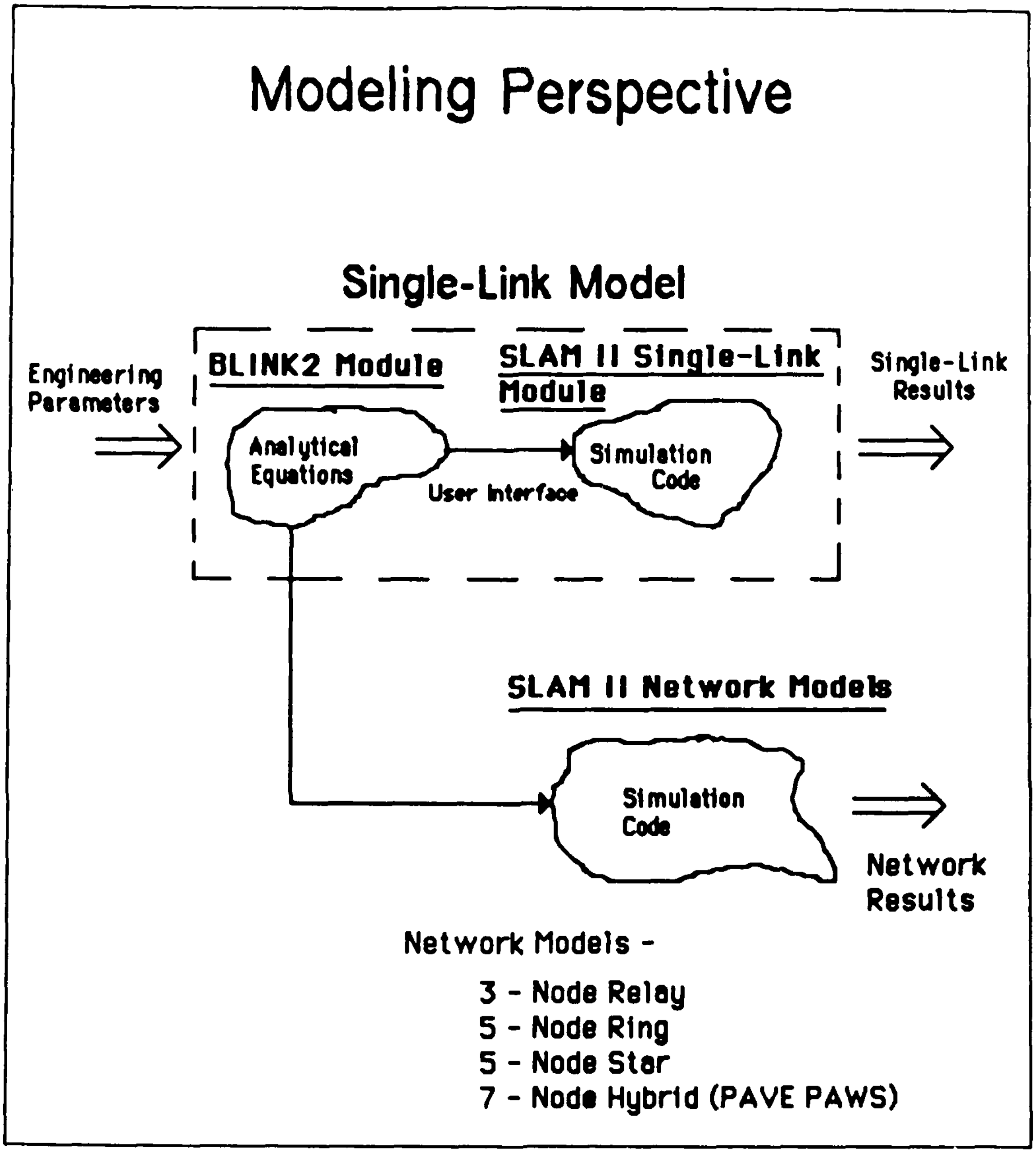


Figure 5.1. Modeling Perspective

written in Borland's Turbo Pascal version 4.0 and is used as the front-end module for this computer model. BLINK2 is designed to satisfy objective 1 from Table 1.1.

The BLINK model was chosen as a baseline because it is conceptually and computationally simple without unnecessary loss of accuracy. A version of the BLINK model is also compatible with the IBM XT/AT which increases its usefulness for this modeling perspective. The CSC model designed by David Brown is another MBC model compatible with the IBM XT/AT. This model is probably more accurate than BLINK, but it is proprietary and has less file and screen manipulation capabilities. The objective of this thesis was to demonstrate a modeling perspective. The results generated by BLINK were considered sufficient for this objective.

The majority of the changes made to BLINK consisted of screen and file manipulation and adding equations derived by Abel, Brown, and Morin [Abe86, BrW78, Mor85]. The equations used in BLINK2 are included in Appendix B. The changes to the screen and file usage were made to provide a more user-friendly interface and an additional interface with the SLAM II single-link simulation module. Upgrading BLINK from Borland's Turbo Pascal version 3.0 to version 4.0 helped make this possible.

Most of the additional capabilities of BLINK were maintained in BLINK2. These additional capabilities include the optional nuclear environment calculations and the VHF troposcatter and LOS/diffraction propagation calculations. These routines, however, were not used in this modeling perspective. Refer to the *Technical Reference Manual and*

User's Guide for the Meteor Burst LINK Program (BLINK) for a complete description of these capabilities [IBM86].

BLINK2 uses a number of engineering parameters to generate meteor trail interarrival time, meteor trail duration, and message duration. BLINK2 uses both overdense and underdense trails to calculate meteor trail interarrival time. However, overdense trails are modeled as underdense to calculate meteor trail duration. The message duration is a function of message size, transmitter bit rate, and propagation delay.

The engineering parameters are input to BLINK2 through the use of an input data file. Appendix D contains a sample BLINK2 input data file. Data files were used instead of an interactive approach because of the number of parameters needed by BLINK2. Separate data files can also be maintained for different MBC networks.

BLINK2 reads the input data file to determine the number of nodes in the network, the network topology, the hour of the day, the month of the year, and necessary engineering parameters. The first value in the data file is the number of nodes in the network. A description of each node including name, latitude, and longitude follows. BLINK2 calculates range between nodes by converting latitude and longitude coordinates to kilometers. A description of these parameters is provided in Appendix D. Significant BLINK2 input parameters are listed in Figure 5.2.

SLAM II Single-Link Module

A SLAM II single-link module was created which satisfies objective 2 from Table 1.1. This module uses the values of meteor trail interarrival time, meteor trail duration, and message duration calculated by BLINK2. The SLAM II module also requires values for message arrival rate, probe response delay, the number of message bits, and the desired transmission protocol.

Two versions of the single-link module were created. The first version simulates Protocol 1 transmission. The second version simulates Protocol 2 transmission. These two versions satisfy objective 3 from Table 1.1. The code for both versions is included in Appendix E.

The SLAM II single-link module provides output values for:

- average buffer size,
- message buffer delay,
- message waiting time,
- message transmission time,
- the number of meteor trails required per message,
- and throughput.

Average buffer size is a measure of the number of messages waiting to be transmitted as a function of time. Message buffer delay is the time a message waits in the buffer until it begins transmission. Message transmission time is the time required to transmit a message. Message waiting time is the total time a message spends in the system which includes buffer delay and transmission time.

The number of meteor trails per message is calculated as the ratio of the total number of meteor trails required to transmit a fixed number of messages. The throughput values are for long-term average throughput. Throughput is calculated as the total number of bits divided by total time. Throughput calculations take into consideration the time between message arrivals and the time between meteor trail arrivals.

The single-link modeling process is summarized in Figure 5.1 and Figure 5.2. WTREL represents waiting time reliability level which is described in Appendix D. Appendix E contains a description of the single-link module and source code.

Single-Link Modeling

BLINK2 Input Parameters

1) Range
2) Frequency
3) Month
4) Hour
5) Transmitter Power
6) Transmitter Gain
7) Receiver Gain
8) Bit Rate
9) Probe Delay
10) Message Bits
11) WTREL
12) Line Losses
13) System Losses
14) Receiver Noise
15) Man-Made Noise
16) Bit Energy to Noise
17) Electron Density
18) Terrain Index

SLAM II Single-Link Module Input Parameters

1) Message Arrival Rate
2) Meteor Trail Interarrival Rate
3) Meteor Trail Duration
4) Message Duration
5) Probe Delay
6) Message Bits
7) Transmission Protocol

SLAM II Single-Link Module Output Values

1) Average Buffer Size
2) Message Buffer Delay
3) Message Waiting Time
4) Transmission Time
5) Trails per Message
6) Throughput

Figure 5.2. Single-Link Modeling Process

SLAM II Network Models

Each transmitter-receiver link in the SLAM II network models were implemented using the single-link module. In addition to the single-link input parameters, a network topology and message routing algorithm must be specified for the network. Four network topologies were simulated:

- a 3-node relay network,
- a 5-node ring network,
- a 5-node star network, and
- a 7-node hybrid network.

These models satisfy objectives 6 and 7 from Table 1.1.

To achieve message routing, a routing table was designed in SLAM II to implement each network topology. The routing table determines which links are used to transmit a message from one node to another. The routing table technique uses static routing which satisfies objective 9 from Table 1.1.

The message routing table is implemented as a NxN table in which N is the number of nodes in the network. The numbers along the side of the routing table specify the transmitting node. The numbers along the top of the routing table specify the final receiver node. Numbers in the table refer to links used to transmit the message.

The diagonal of the table is null indicating that a node can not transmit to itself. A fully-connected network would have a different link number for each element in a row, and the upper and lower triangles would be mirror images when using full-duplex links.

Usually the routing table will have duplicate link numbers across a row indicating that the network is not fully connected. A network with full-duplex links will use the same link number between a pair of nodes. Half-duplex links are implemented by specifying separate link numbers between a pair of nodes.

The BLINK2 module is run for each link in the network to provide meteor trail interarrival time, meteor trail duration, and message duration. In addition, the desired transmission protocol and probe response delay are required for each link in the network. Message size and message arrival rate is required for each transmitter. The network simulation process is summarized in Figure 5.3.

A message transmission table is created for each network to model the message duration values provided by BLINK2. The message transmission table is similar to the message routing table except the link numbers are replaced with the message duration.

A probe delay table is created which has the same size as the routing and transmission tables. The probe delay table is initialized to the probe response delay for each link when using Protocol 2. The table is null for Protocol 1 because the probe response delay is subtracted from the trail duration in the meteor trail arrival process.

Network Modeling

BLINK2 Input Parameters

1) Range
2) Frequency
3) Month
4) Hour
5) Transmitter Power
6) Transmitter Gain
7) Receiver Gain
8) Bit Rate
9) Probe Delay
10) Message Bits
11) WTREL
12) Line Losses
13) System Losses
14) Receiver Noise
15) Man-Made Noise
16) Bit Energy to Noise
17) Electron Density
18) Terrain Index

SLAM II Network Model Input Parameters

1) Message Arrival Rate
2) Message Duration
3) Trail Duration
4) Probe Delay
5) Trail Interarrival Rate
6) Message Bits
7) Transmission Protocol
8) Network Topology
9) Network Routing Table

SLAM II Network Model Output Values

1) Link Throughput
2) Link Waiting Time
3) Link Transmission Time
4) Network Throughput
5) Network Waiting Time

Figure 5.3. Network Modeling Process

See Appendix E for a modeling description of the probe response delay and the meteor trail arrival process.

A separate meteor trail arrival process exists for each link in the network. Each meteor trail arrival process is initialized with the meteor trail interarrival and duration times calculated by BLINK2. The probe response delay in the meteor trail arrival process is initialized to the link probe response delay when Protocol 1 is used. When Protocol 2 is used for message transmission, the probe response delay in the meteor trail arrival process is null.

Relay Network. The relay network consists of three nodes. Figure 5.4 describes the network topology and message routing table for the network.

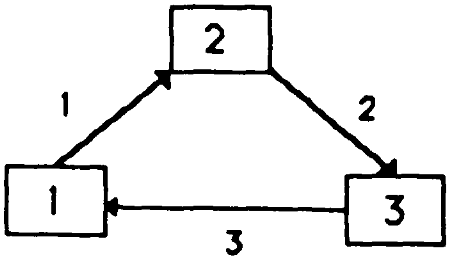
In this network, only nodes 1 and 3 create messages. Node 2 is a relay which receives messages from node 1 and transmits them to node 3. Messages created at node 3 are transmitted directly to node 1.

The topology is represented by arrows and boxes. Link numbers are indicated beside the arrows. Node numbers are inside the box.

In this example, messages created at node 1 with node 3 as final destination must first go to node 2 via link 1. The message is then transmitted from node 2 via link 2 to node 3.

Relay Network

NETWORK TOPOLOGY



MESSAGE ROUTING TABLE

From Node \ To Node	1	2	3
1	--	1	1
2	--	--	2
3	3	--	--

Figure 5.4. Relay Network

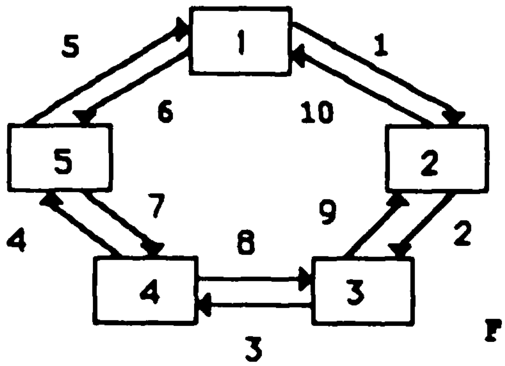
Ring Network. The ring network consists of five nodes which are connected by an inner and outer ring of half-duplex links. Figure 5.5 describes the topology and message routing table for the network.

Each node creates messages. Each message has attributes which indicate the current transmitter and final receiver. When a message is created, the current node is the creation node and the destination node is determined by the network. In this network, message destinations are assigned in the following manner:

Creation Node	*Final Destination Node*
1	3
2	5
3	1
4	1
5	2

Ring Network

NETWORK TOPOLOGY



MESSAGE ROUTING TABLE

To Node

From Node	1	2	3	4	5
1	--	1	1	6	6
2	10	--	2	2	10
3	9	9	--	3	3
4	4	8	8	--	4
5	5	5	7	7	--

Figure 5.5. Ring Network

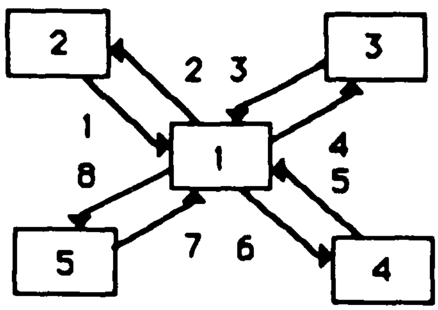
The current transmitter and final receiver nodes are used as indexes into the message routing table to determine the transmission link. After transmitting the message, the link used to transmit the message is used to determine the new transmitter node. Messages are transmitted until the current transmitter node equals the final receiver node. Protocol 1 is used for all links in this network.

Star Network. The star network is composed of five nodes and eight links. Figure 5.6 describes the network topology and message routing table for the star network.

All nodes create messages except for node 1. Node 1 is used to relay messages between the other nodes. Any node can transmit to any other node using exactly two links.

Star Network

NETWORK TOPOLOGY



MESSAGE ROUTING TABLE

To Node

From Node	1	2	3	4	5
1	--	2	4	6	8
2	1	—	1	1	1
3	3	3	--	3	3
4	5	5	5	--	5
5	7	7	7	7	--

From Node

Figure 5.6. Star Network

Each node has one in-link and one out-link except for node 1.

Message destinations are assigned in the following manner:

Creation Node	*Final Destination Node*
2	3
3	4
4	5
5	2

Links 1-4 use Protocol 2 for message transmission. Links 5-8 use Protocol 1 for message transmission.

Hybrid Networks. Two hybrid networks are described. Both hybrid networks implement an arbitrary MBC network of PAVE PAWS sites.

PAVE PAWS is a Phased Array Warning System used to provide early warning of a SLBM (Submarine Launched Ballistic Missile) attack. These PAVE PAWS sites send SLBM warning information, satellite tracking information, and site status information to several data users. For the purpose of this arbitrary network, the data users will consist of the NORAD Cheyenne Mountain Complex and the SAC underground command post located at Omaha AFB.

A network model is provided for the first PAVE PAWS network. The second PAVE PAWS network is used to discuss additional modeling techniques.

PAVE PAWS Network 1. The first network has seven nodes and eight links. Figure 5.7 illustrates the network topology. The message routing table is provided in Figure 5.8. The simulation code is included in Appendix F. This network model uses a link range table instead of a message transmission table. Message duration per link is calculated from the range table.

Beale AFB, Goodfellow AFB, Otis AFB, and Robins AFB have PAVE PAWS sites. The NORAD Cheyenne Mountain Complex and Omaha AFB are data users. One relay is used in the network.

Each of the PAVE PAWS sites generate messages. These messages have a Poisson distribution (i.e. exponential interarrival time). These messages represent missile warning information, satellite tracking information, and

site status information sent to the two data users. Each data user receives the same PAVE PAWS message. This is accomplished by selecting the final destination node to be the furthest data user from the transmitting PAVE PAWS site. Message destinations are assigned in the following manner:

Creation Node	*Final Destination Node*
Beale	Omaha
Goodfellow	Cheyenne Mountain
Goodfellow	Omaha
Otis	Cheyenne Mountain
Robins	Cheyenne Mountain

Messages created at the PAVE PAWS sites have 520 bits.

Cheyenne Mountain also generates messages. Messages are created once every ten minutes. These messages have the following destinations:

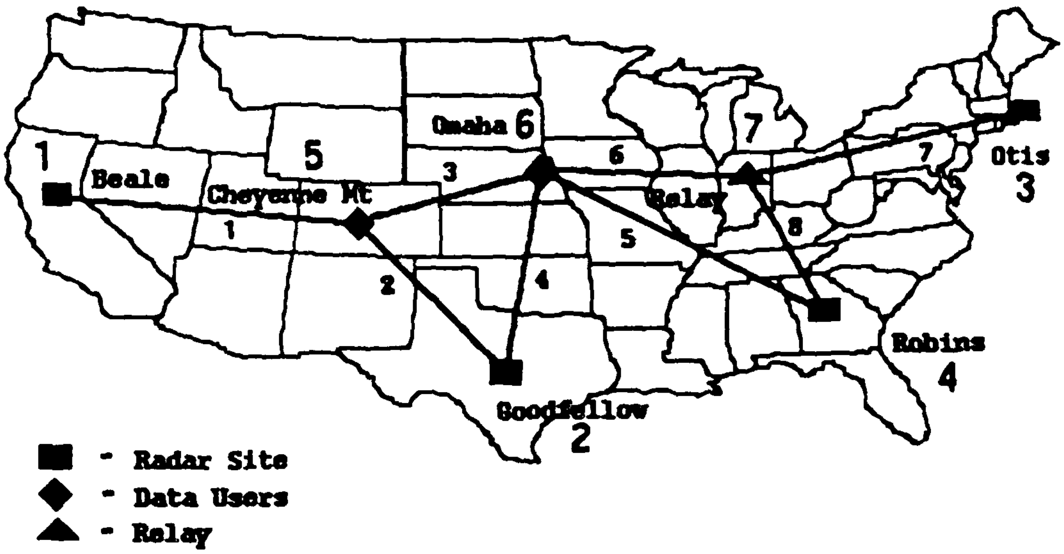
Creation Node	*Final Destination Node*
Cheyenne Mountain	Beale
	Goodfellow
	Otis
	Robins

Messages created at Cheyenne Mountain represent status information transmitted to each PAVE PAWS site. These messages contain 132 bits.

Messages created at Cheyenne Mountain have a deterministic distribution. Other distributions which SLAM II provides include:

- Erlang,
- Gamma,
- Poisson,
- Normal,
- Lognormal,
- Triangular,
- Uniform, or
- Weibull [Pri86].

PAVE PAWS Meteor Burst Network 1



Network Topology

Site	Node	Latitude	Longitude
Beale	1	39.20	121.50
Goodfellow	2	31.40	100.40
Otis	3	41.70	70.50
Robins	4	32.60	83.60
Cheyenne	5	38.80	104.80
Omaha	6	41.20	96.00
Relay	7	41.00	87.00

Total Number of Links = 8

Figure 5.7. PAVE PAWS Network 1

MESSAGE ROUTING TABLE

To Node

From Node	1	2	3	4	5	6	7
1	--	--	--	--	1	1	--
2	--	--	--	--	2	4	--
3	--	--	--	--	7	7	7
4	--	--	--	--	5	5	--
5	1	2	3	3	--	3	--
6	--	--	6	5	3	--	--
7	--	--	7	--	6	6	--

Figure 5.8. Message Routing Table for PAVE PAWS Network 1

PAVE PAWS Network 2. The second PAVE PAWS network is created by adding three additional relays to the first network. The second PAVE PAWS network has 10 nodes and 19 links. Figure 5.9 describes the network topology.

The additional relays were added to provide multiple paths from each PAVE PAWS site to the two data users. This network is used to discuss adaptive message routing, flood routing, and priority message traffic.

Additional Modeling Techniques

The modeling perspectives used to create these network models can be used to simulate many other MBC networks. Several additional modeling techniques are discussed to illustrate the possibilities.

Overdense Meteor Trails. Objective 5 from Table 1.1 was to demonstrate how overdense meteor trails could be simulated. A single-link simulation example which models overdense and underdense meteor trails is provided in Appendix E.

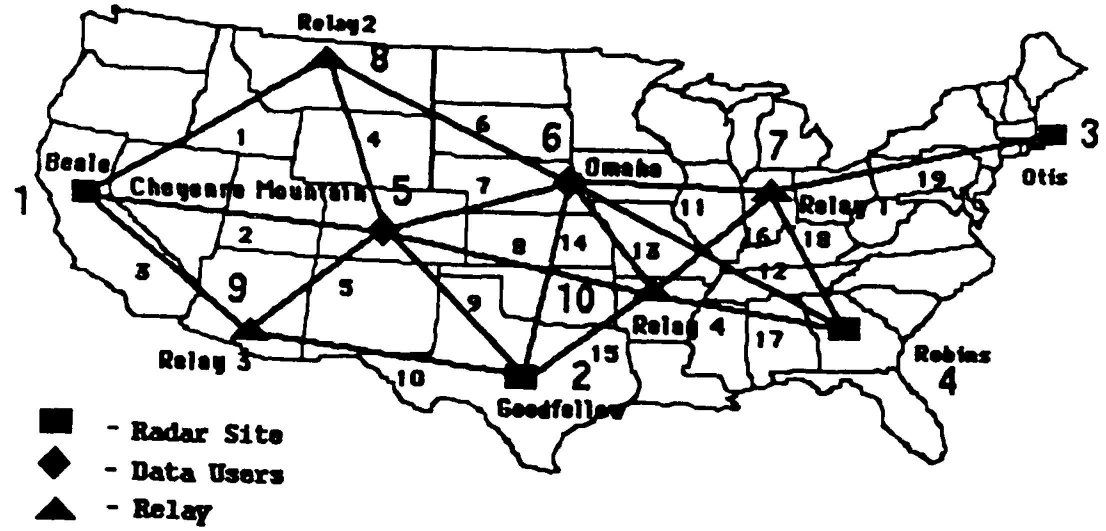
Meteor trail interarrival time is chosen to be the interarrival time of an underdense meteor trail. Meteor trail duration is simulated as overdense 10 percent of the time and underdense 90 percent of the time. An exponential distribution for overdense trail duration is used.

Adaptive Routing. Objective 10 from Table 1.1 was to discuss adaptive routing. Adaptive routing dynamically updates the message routing table based on the state of the network.

To implement adaptive routing, the link numbers in the message routing table would be changed when the link approaches saturation. To determine when a link is becoming saturated, the SLAM II NNQ function could be used to determine the number of messages waiting to be transmitted over the link [Pri86]. To change the link numbers in the message routing table, Fortran subroutines could be created and linked with the SLAM II network model.

The second PAVE PAWS network provides a good example for discussing adaptive message routing. Each of the PAVE PAWS sites except Otis has three or more possible links to

PAVE PAWS Meteor Burst Network 2



Network Topology

Site	Node	Latitude	Longitude
Beale	1	39.20	121.50
Goodfellow	2	31.40	100.40
Otis	3	41.70	70.50
Robins	4	32.60	83.60
Cheyenne	5	38.80	104.80
Omaha	6	41.20	96.00
Relay1	7	41.00	87.00
Relay2	8	48.00	108.00
Relay3	9	32.00	111.00
Relay4	10	36.00	93.00

Total Number of Links = 19

Figure 5.9. PAVE PAWS Network 2

transmit messages. The primary transmission link for each site would be indicated in the message routing table. If the primary link becomes saturated, a link to one of the relay nodes would replace the primary link in the message routing table.

Flood Routing. Objective 11 from Table 1.1 was to discuss flood routing. In basic flood routing, every incoming message is retransmitted on every outgoing link except the link the message arrived on. Flood routing can not be implemented using a message routing table. Only one link can be specified between two nodes using the message routing table.

To implement flood routing, an additional table could be created with a row for each node. Each row would contain all links a node could use for transmission. When a message is received, it would be retransmitted on all links in the row except for the link the message arrived on.

The second PAVE PAWS network provides a excellent topology for flood routing. Messages created at each PAVE PAWS site would be transmitted on all possible links. Messages would be terminated when arriving at one of the data users. Hop counters and "drop dead" times could be used to control the number of messages in the network.

Selective flooding is slightly more practical than basic flooding. To implement selective flooding, the

receiving node would only retransmit on links going in the direction of the data users.

Priority Messages. Objective 12 from Table 1.1 was to discuss priority messages. Priority message traffic can be easily simulated using SLAM II. A PRIORITY statement can be used in the network model to assign different priorities to messages. A PRIORITY statement specifies the service discipline for messages waiting in a transmission buffer. Service disciplines include:

- FIFO (First-In First-Out),
- LIFO (Last-In First-Out),
- HVF (High Value First), or
- LVF (Low Value First).

HVF and LVF would be used for priority messages. The value used for determining priority would be assigned as a message attribute.

The second PAVE PAWS network is used to discuss priority message traffic. Messages created at the PAVE PAWS sites can be grouped into priorities. Missile warning messages would have the greatest priority. Satellite tracking information would have the next highest priority, and site status information would have the lowest priority. Messages created at Cheyenne Mountain would have the same priority as site status information.

When a missile warning message is created, it would be transmitted before all satellite tracking messages and site status messages already waiting in the transmission buffer.

Messages of equal priority would be transmitted according to a FIFO queueing discipline.

The results from the single-link and network models are provided in Chapter VI. Chapter VI compares BLINK2 results to empirical data. The delay and throughput results of the single-link simulation module are compared to analytical results.

VI. *Modeling Results*

Introduction

This chapter compares empirical data for meteor arrival rate with results from BLINK and BLINK2. This chapter also validates the delay and throughput results of the SLAM II single-link module.

The SLAM II single-link module was validated by comparing the simulation results for Protocols 1 and 2 with analytical results produced by BLINK2. Validating the SLAM II module satisfies objective 4 from Table 1.1. Simulation results are presented for each of the network models. These results are used to demonstrate performance characteristics of MBC.

Empirical Results for Meteor Arrival Rate

Empirical data for meteor arrival rate is compared to predicted results from BLINK and BLINK2 in Figure 6.1 and Figure 6.2. The empirical data is from the RADC high-latitude MBC link in Greenland [IBM85, IBM86]. RSL is the received signal level in dBm, and it is a measure of the minimum receiver detection threshold. The number of detected meteor trails decreases as RSL increases.

45.0	1	FREQUENCY (30..120) (MHz)
12	2	MONTH OF THE YEAR (1...12)
11	3	HOUR OF THE DAY (0...23)
800.0	4	TRANSMISSION POWER (Watts)
10.0	5	TRANSMITTER ANTENNA GAIN (dBi)
10.0	6	RECEIVER ANTENNA GAIN (dBi)
21141	7	TRANSMITTER BIT RATE (bps)
38.7	8	PROBE RESPONSE DELAY (msec)
864	9	NUMBER OF BITS IN MESSAGE
0.95	10	WAITING TIME RELIABILITY LEVEL
1.0	11	LINE LOSSES (dB)
1.0	12	SYSTEM LOSSES (dB)
4.0	13	RECEIVER NOISE (dB)
1	14	MAN-MADE NOISE FACTOR (1=GAL 2=QUIET 4=RURAL 10=SUB)
8.5	15	BIT ENERGY TO NOISE (dB)
0		TERRAIN INDEX (0,1,2,3)
1260.0		RANGE (km)

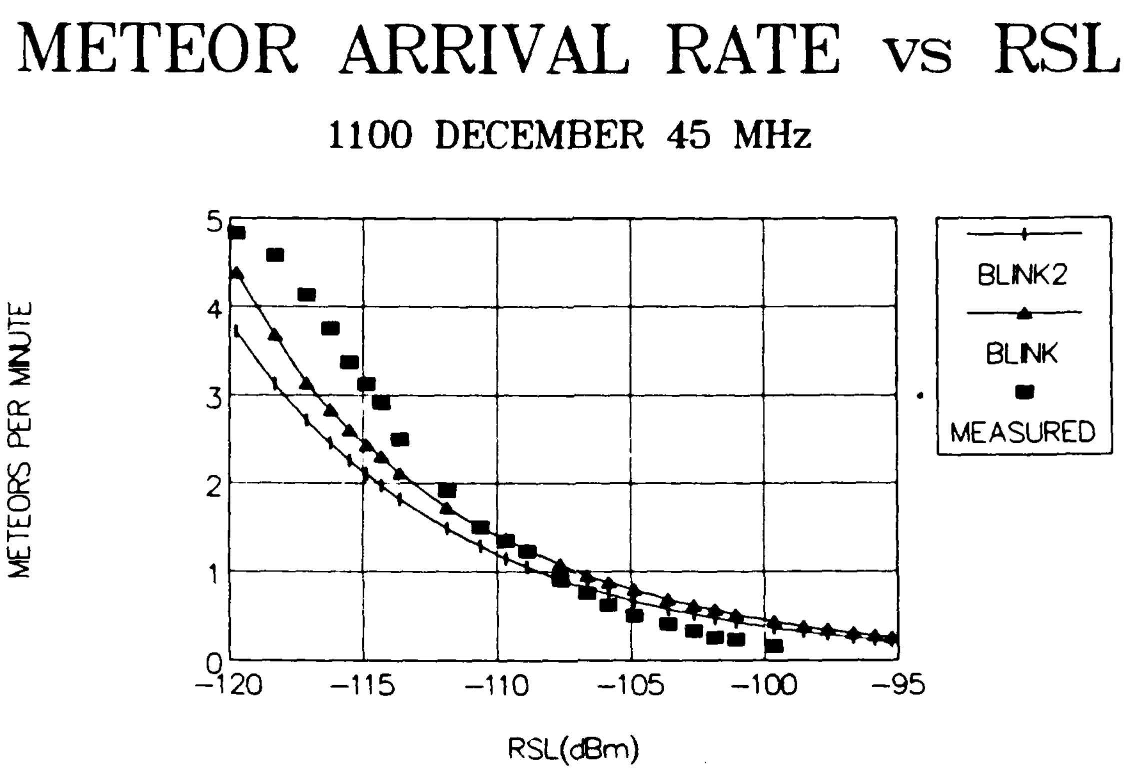


Figure 6.1. Meteor Arrival Rate at a Frequency of 45 MHz

104.0	1	FREQUENCY (30..120) (MHz)
12	2	MONTH OF THE YEAR (1...12)
11	3	HOUR OF THE DAY (0...23)
800.0	4	TRANSMISSION POWER (Watts)
10.0	5	TRANSMITTER ANTENNA GAIN (dBi)
10.0	6	RECEIVER ANTENNA GAIN (dBi)
21141	7	TRANSMITTER BIT RATE (bps)
38.7	8	PROBE RESPONSE DELAY (msec)
864	9	NUMBER OF BITS IN MESSAGE
0.95	10	WAITING TIME RELIABILITY LEVEL
1.0	11	LINE LOSSES (dB)
1.0	12	SYSTEM LOSSES (dB)
4.0	13	RECEIVER NOISE (dB)
1	14	MAN-MADE NOISE FACTOR (1=GAL 2=QUIET 4=RURAL 10=SUB)
8.5	15	BIT ENERGY TO NOISE (dB)
0		TERRAIN INDEX (0,1,2,3)
1260.0		RANGE (km)

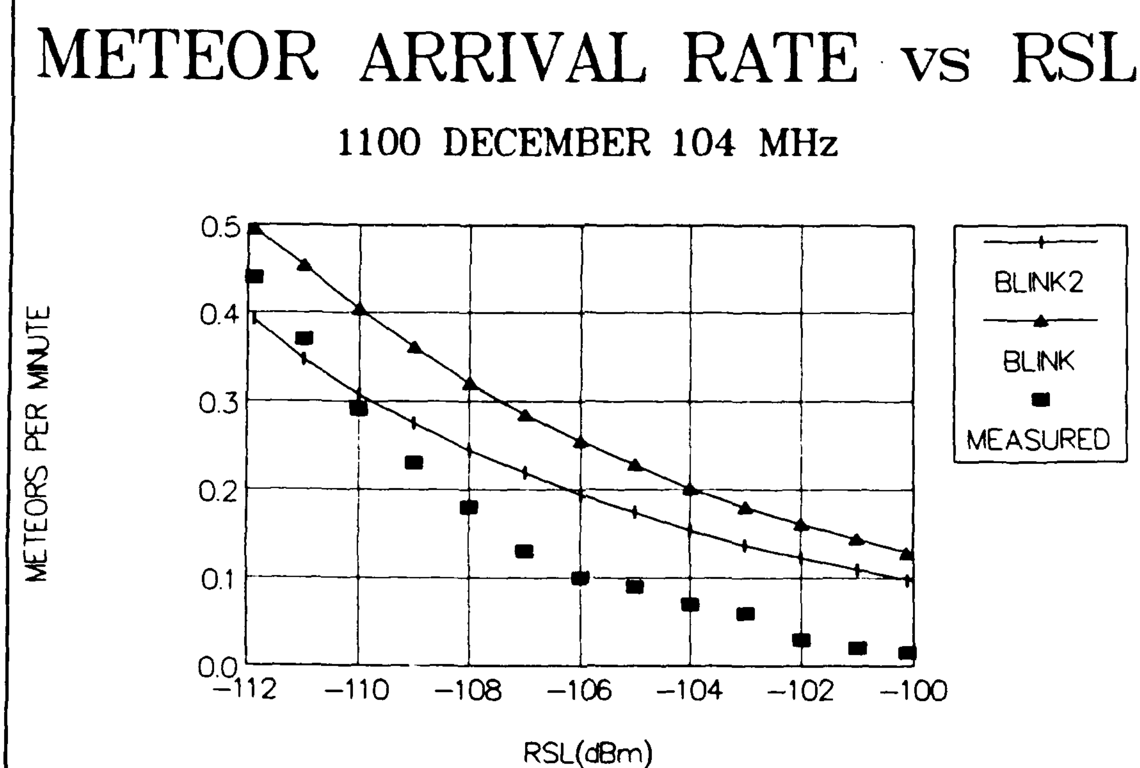


Figure 6.2. Meteor Arrival Rate at a Frequency of 104 MHz

Figure 6.1 presents results for a transmitter frequency of 45 MHz. For RSL levels less than -110 dBm, BLINK predictions are closer to empirical data than BLINK2. Both BLINK and BLINK2 predictions are very close to empirical data for RSL levels greater than -110 dBm.

Figure 6.2 presents meteor arrival results using a transmitter frequency of 104 MHz. At this frequency, BLINK2 predictions are closer to empirical data than BLINK. BLINK2 provides optimistic results for RSL levels greater than -110 dBm.

Delay and Throughput Validation

Throughput calculated by BLINK2 for Protocol 1 and a modification of Protocol 2 were used to validate the simulation throughput results. However, only the modified Protocol 2 was used to validate the simulation delay results.

Milstein derived equations describing throughput for Protocol 1 and the modified Protocol 2 [Mil86, Mil87]. These equations assume maximum transmitter utilization.

Delay equations for the modified Protocol 2 were described in Chapter 5 [IBM86]. These equations included the effects of message arrival rate and modeled the message transmission process as a M/G/1 queue. Time between meteor trails was assumed to be exponential with parameter AMBPM. The Laplace transform of the distribution of message

transmission time was used to calculate delay. Equation 10 was used to validate the SLAM II single-link module.

Results for Protocol 1 delay were derived by Oetting [Oet79]. These results, however, do not consider message arrival rate and were not used to validate the SLAM II single-link module.

Protocol 1 Validation. Equation 36 from Appendix B describes Protocol 1 throughput. This equation calculates maximum possible throughput and represents an upper bound asymptote for the SLAM II results.

There are two methods of modeling message transmission using Protocol 1. The first method considers messages as distinct groups of bits with an associated message duration. The second method removes the distinction between messages, and considers messages as one single collection of bits. When the second method is used, the trail duration is substituted for the message duration in the throughput equation.

Table 6.1 presents results for analytical throughput for methods 1 and 2 and simulation throughput in bps. METHOD 1 % and METHOD 2 % represent agreement between simulation and analytic results in percentage. BDUR refers to the meteor trail duration, and MDUR refers to the message duration.

Simulation results were calculated from two antithetic and two non-antithetic runs. The following input values were used for the SLAM II single-link module:

Meteor Trail Interarrival Rate = 15.266 sec,
Transmitter Bit Rate = 8000 bps,
Message Duration = 0.138 sec,
Probe Response Delay = 0.030 sec, and
Message Bits = 1024

Comparison of analytical and simulation results indicated that method 2 is more accurate than method 1 when the ratio of meteor trail duration to message duration exceeds a value of six.

Table 6.1. Protocol 1 Throughput Analysis

BDUR/ MDUR	MSGS/ MIN	SIM TPUT	METHOD 1 TPUT	METHOD 2 TPUT	METHOD 1 %	METHOD 2 %
2	6	96	77	93	80	97
3	10	158	119	158	75	100
4	14	222	162	224	73	99
5	17	267	204	291	76	92
6	19	299	246	358	82	84
7	21	329	288	425	88	77
8	23	363	330	492	91	74
10	27	431	414	626	96	69
20	49	775	835	1298	93	60

Protocol 2 Validation. Analytical results for Protocol 2 assume only one meteor trail is used for message transmission. If a message completes transmission before the meteor trail disappears, a new meteor trail must be acquired for the next message.

This represents an artificial constraint on the message transmission process. In reality, an existing

meteor trail could be re-acquired after transmitting a message and considered a new trail. The SLAM II single-link module models the process in this manner. Deviations from the simulation and analytical results become larger as the ratio of meteor trail duration to message duration becomes larger.

To validate Protocol 2, a modification was made to the single-link module. Additional delay was added to the message transmission process which is composed of the difference between the trail duration and the message duration time and the next meteor trail interarrival time. This additional delay was added 50 percent of the time. This modification will be referred to as Protocol 2a. The code for this modification is included in Appendix E. Equation 38 in Appendix B is used to calculate Protocol 2a throughput. This equation calculates maximum throughput assuming maximum transmitter utilization.

Figure 6.3 includes a graph of throughput for Protocols 1 and 2. For Protocol 1, messages are considered as distinct entities with an associated message duration. Figure 6.4 includes a graph of Protocol 2a throughput. The dashed horizontal lines indicate analytical throughput.

Figure 6.5 includes a graph of message delay for Protocols 1 and 2. Figure 6.6 includes a graph of analytical message delay and Protocol 2a message delay. The dashed vertical lines indicate maximum transmitter

capability. As the message arrival rate approaches the maximum transmitter capability, infinite message delay results which the simulation model can not accurately predict. These points are circled in Figures 6.5 and 6.6.

Throughput and delay values were averaged from two antithetic and two non-antithetic simulation runs. The simulation input values were selected from the Beale-Cheyenne Mountain transmission link from the first PAVE PAWS network described in Chapter 5. These input values are:

Meteor Trail Interarrival Rate	=	15.266 sec,
Meteor Trail Duration	=	0.450 sec,
Transmitter Bit Rate	=	8000 bps,
Message Duration	=	0.138 sec,
Probe Response Delay	=	0.030 sec, and
Message Bits	=	1024

The simulation results closely map to asymptotic bounds described by analytic equations.

MSGS/MIN	PROTOCOL 1 THROUGHPUT (bps)	PROTOCOL 2 THROUGHPUT (bps)
0.5	8	8
1.0	16	16
2.0	32	32
3.0	49	49
4.0	65	64
5.0	81	80
6.0	97	96
7.0	113	108
8.0	129	116
9.0	144	115
10.0	159	116
11.0	172	
12.0	181	
13.0	188	
14.0	184	

ANALYTICAL THROUGHPUT FOR PROTOCOL 1 = 175 bps

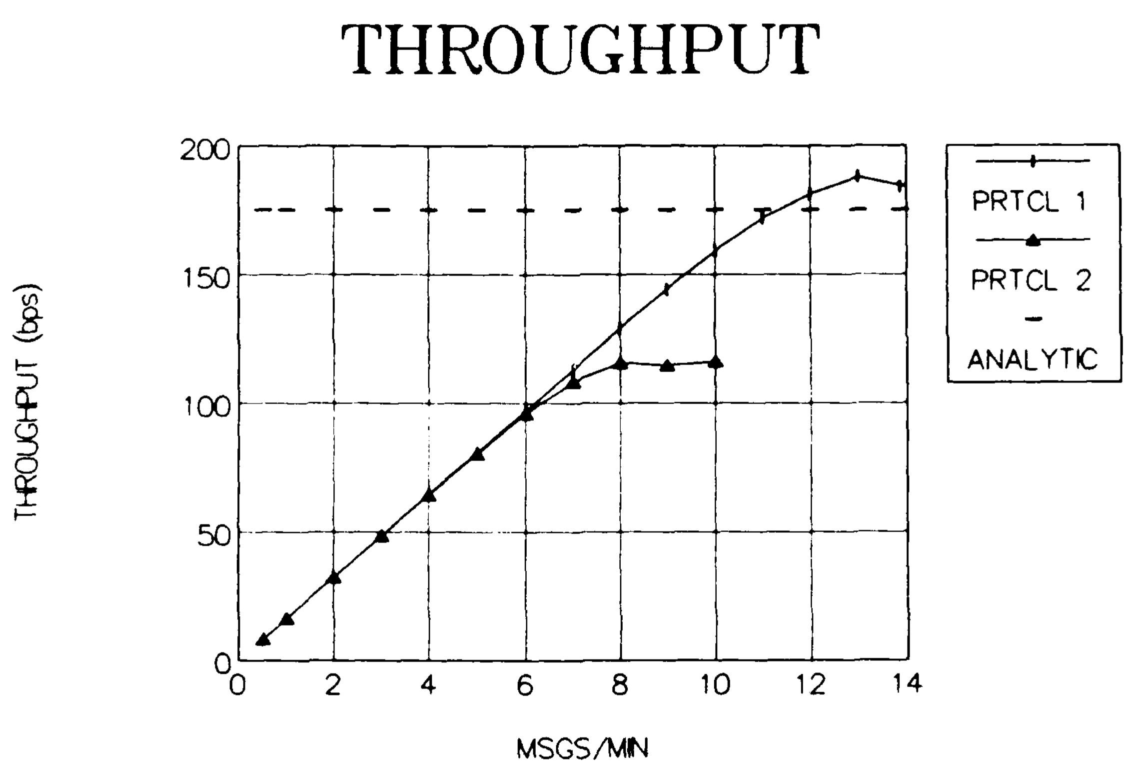


Figure 6.3. Throughput for Protocols 1 and 2

MSGS/MIN	PROTOCOL 2a THROUGHPUT (bps)
0.25	4.1
0.50	8.3
0.75	12.3
1.00	16.8
1.25	20.3
1.50	24.7
1.75	28.7
2.00	32.4
2.25	37.3
2.50	41.7
2.75	43.8
3.00	43.2
4.00	45.6
5.00	45.1

ANALYTICAL THROUGHPUT FOR PROTOCOL 2a = 43 bps

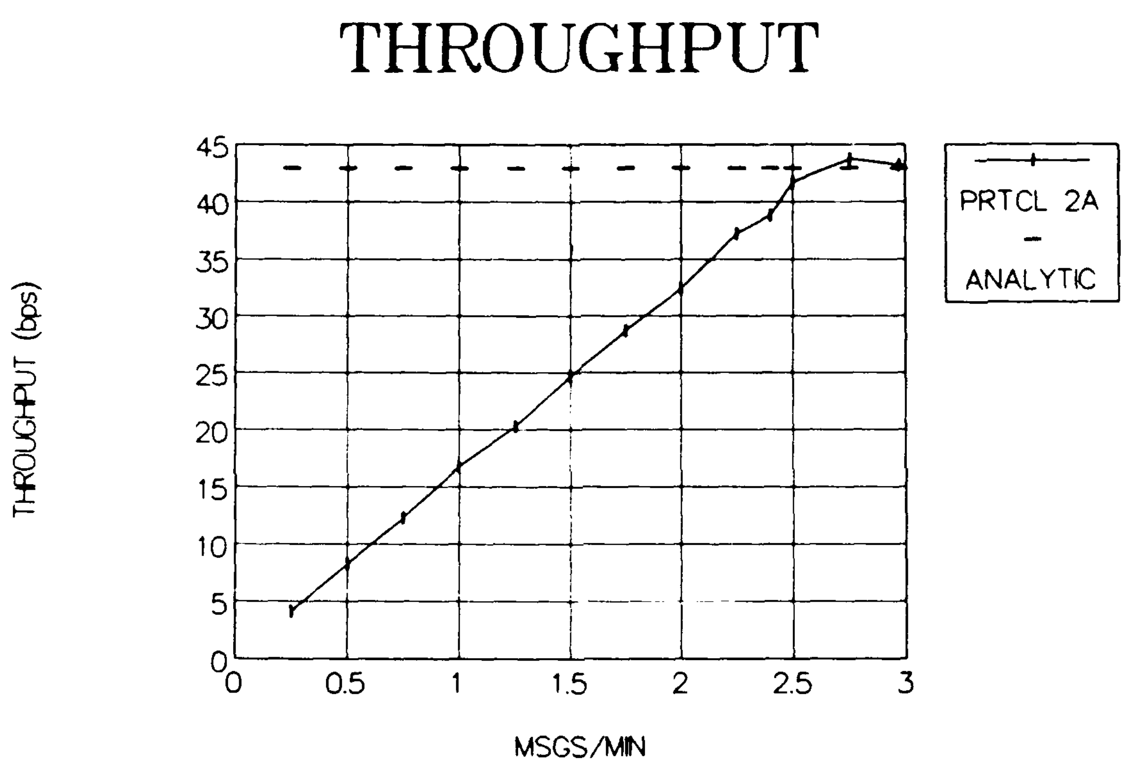


Figure 6.4. Throughput for Protocol 2a

MSGS/MIN	PROTOCOL 1 MESSAGE DELAY (sec)	PROTOCOL 2 MESSAGE DELAY (sec)
0.5	3.3	3.9
1.0	6.1	9.0
2.0	12.4	18.6
3.0	15.7	26.3
4.0	19.4	39.0
5.0	25.0	56.8
6.0	29.0	98.0
7.0	32.5	254.3
8.0	46.4	345.5
9.0	56.4	
10.0	77.1	
11.0	113.8	
12.0	175.7	
13.0	209.8	
14.0	239.5	

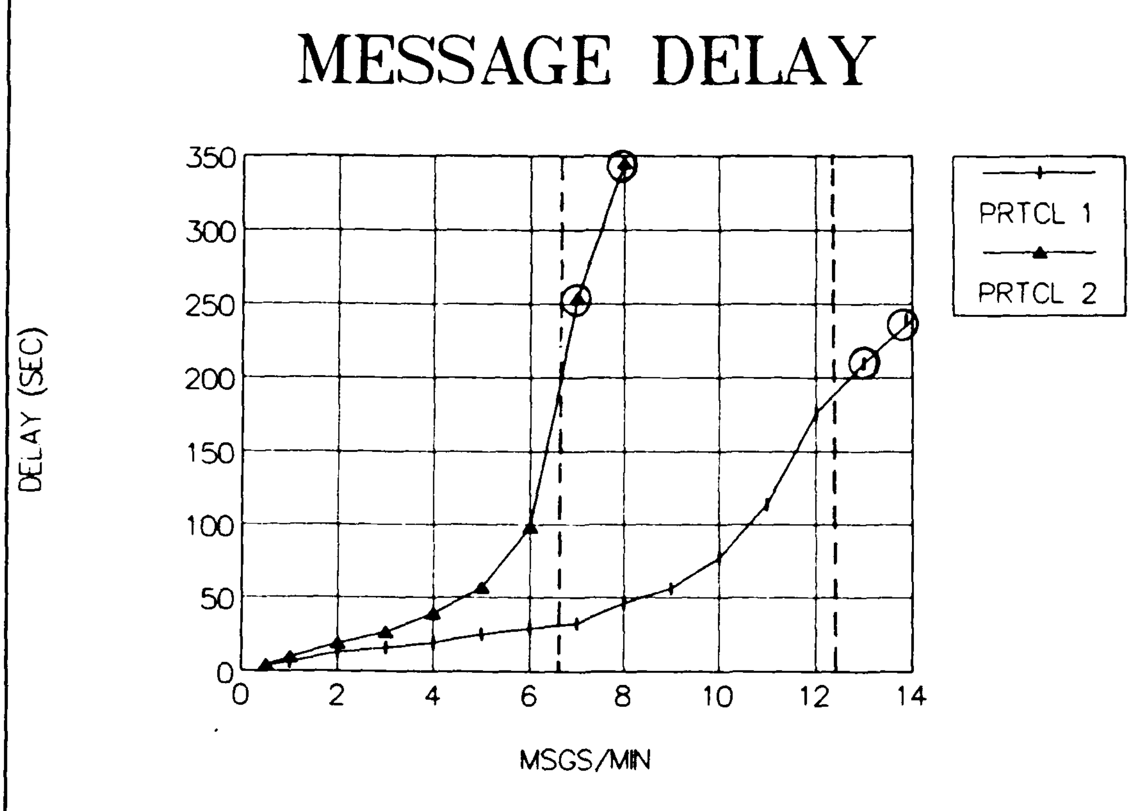


Figure 6.5. Message Delay for Protocols 1 and 2

MSGS/MIN	ANALYTICAL MESSAGE DELAY (sec)	PROTOCOL 2a MESSAGE DELAY (sec)
0.25	2.5	4.3
0.50	5.5	9.0
0.75	9.4	15.4
1.00	14.5	22.8
1.25	21.4	28.6
1.50	31.5	46.4
1.75	47.5	58.6
2.00	76.8	83.5
2.25	147.3	175.5
2.50	272.7	398.0
2.75	557.2	806.3

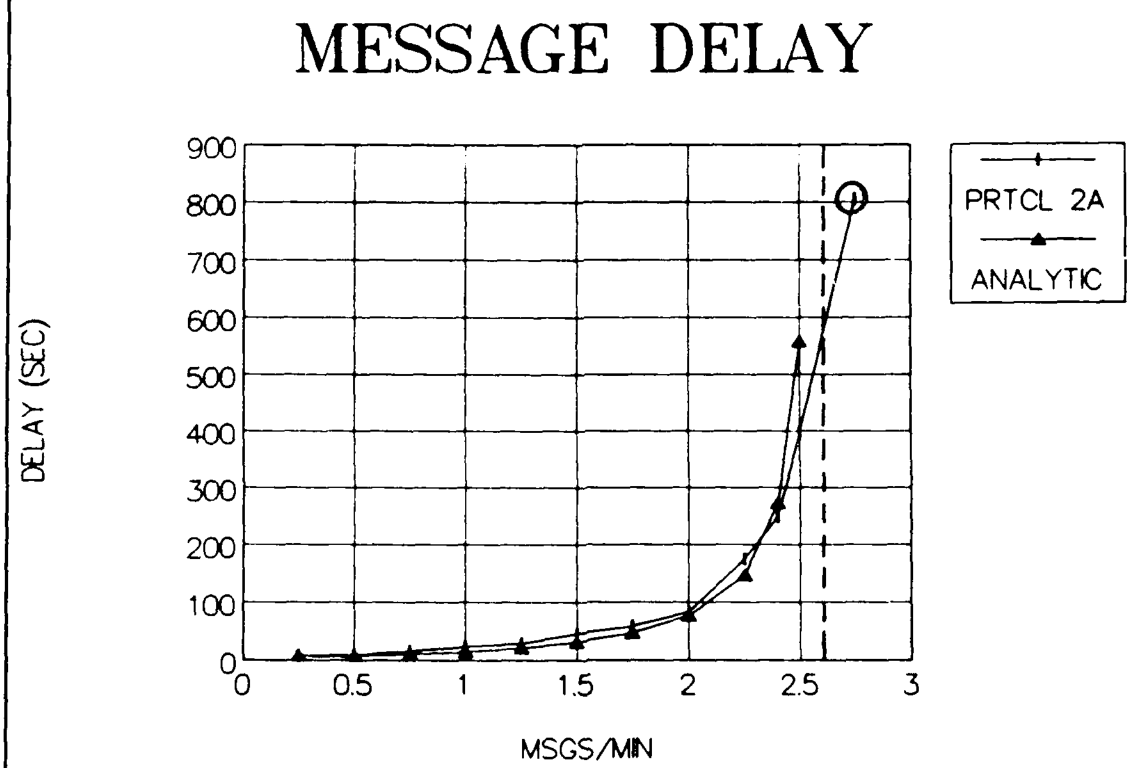


Figure 6.6. Analytical Message Delay and Protocol 2a Message Delay

SLAM II Network Model Results

Results for each of the network models are given. BLINK2 input parameters and the SLAM II network input parameters are specified for each link. However, only output for designated links is provided. Output from each model was chosen to demonstrate MBC performance issues. SLAM II run time results are provided in Appendix H.

Relay Network. Input values for the relay network were chosen to illustrate the effect range has on MBC performance. Two antithetic and two non-antithetic simulation runs were made to calculate the output values.

Figure 6.7 repeats the relay network topology and message routing table. Table 6.2 lists the BLINK2 input parameters. Table 6.3 includes the SLAM II network input parameters, and Table 6.4 lists selected output values.

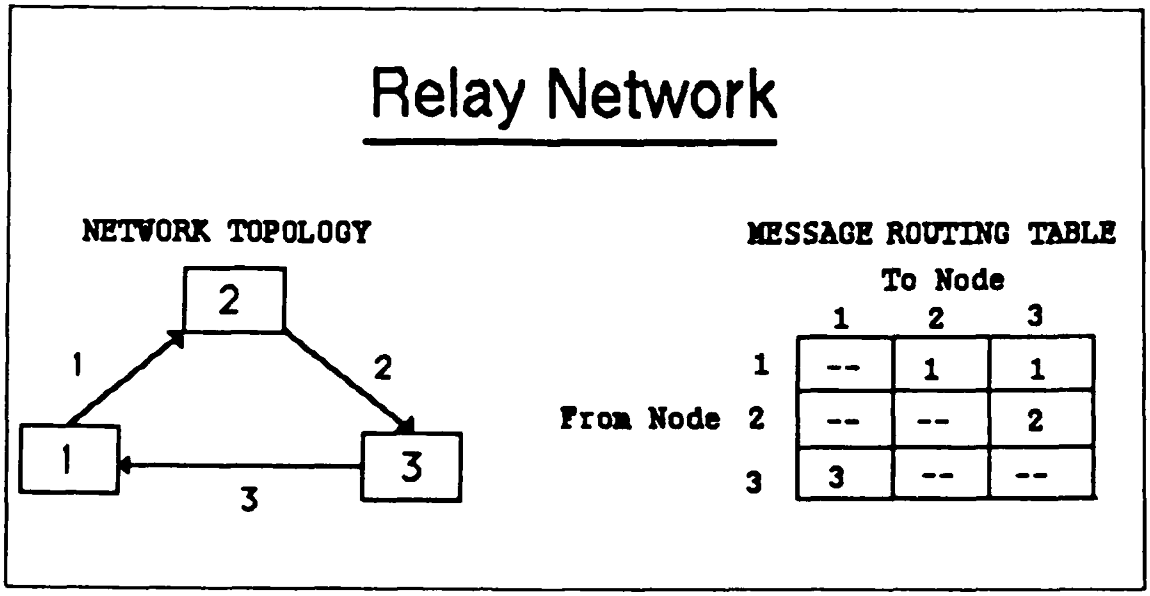


Figure 6.7. Relay Network

Table 6.2. BLINK2 Input Parameters for the Relay Network

	LINK 1	LINK 2	LINK 3
1) Range (km)	1000	100C	300
2) Frequency (MHz)	50	50	50
3) Month	May	May	May
4) Hour	1100	1100	1100
5) Transmitter Power (W) .	1000	1000	1000
6) Transmitter Gain (dBi)	10	10	10
7) Receiver Gain (dBi) .	10	10	10
8) Transmitter Bit Rate (bps)	2000	2000	2000
9) Probe Response Delay (sec)	0.02	0.02	0.02
10) Message Bits	406	406	406
11) Line Losses (dB) . . .	1.00	1.00	1.00
12) System Losses (dB) . .	1.00	1.00	1.00
13) Receiver Noise (dB) . .	4.00	4.00	4.00
14) Man Made Noise Factor .	1	1	1
15) Bit Energy to Noise (dB)	9.0	9.0	9.0
16) Terrain Factor	0	0	0
17) Electron Line Density (el/m)	$5x10^{13}$	$5x10^{13}$	$5x10^{13}$

Table 6.3. SLAM II Relay Network Input Parameters

	NODE 1	NODE 2	NODE 3
1) Message Arrival Rate (msgs/min)	3	0	3
	LINK 1	LINK 2	LINK 3
2) Trail Interarrival Rate (sec)	6.446	6.446	14.967
3) Trail Duration (sec)	0.949	0.949	0.348
4) Message Duration (sec) . . .	0.210	0.210	0.205
5) Probe Response Delay (sec) .	0.020	0.020	0.020
6) Message Bits	406	406	406
7) Transmission Protocol	1	1	1

Table 6.4. SLAM II Relay Network Output Values

	LINK 1	LINK 2	LINK 3
1) Transmission Time (sec)	5.7	5.1	14.2
		LINKS 1&2	LINK 3
2) Message Waiting Time (sec)		15.8	43.9
3) Throughput (bps)		19.5	22.3

Throughput results for link 3 and links 1&2 are nearly the same. However, message delay for link 3 is more than twice the delay experienced by transmitting over both link 1 and link 2. This result demonstrates the importance of network topology on message waiting time and satisfies objective 8 from Table 1.1.

MBC performance is maximized at ranges around 1000 km. Shorter or longer links are less efficient and experience greater message delay. This result is demonstrated in Appendix C.

Adding relays to a MBC network to achieve links of 1000 km may improve performance. Other considerations, however, include the increased system overhead and queueing delay caused by adding additional relay transmitters. Simulation can be used to analyze all of these effects on network performance.

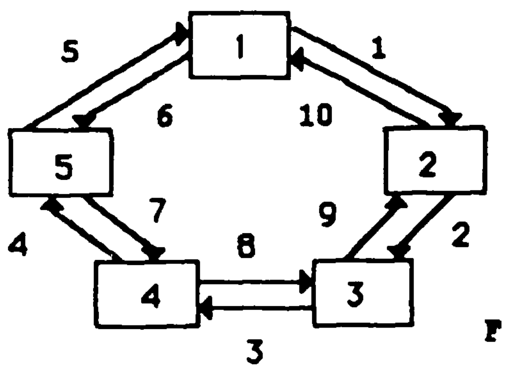
Ring Network. Input values for the ring network were chosen to demonstrate the effect of transmitter frequency on MBC performance. Two antithetic and two non-antithetic

simulation runs were made to calculate selected output values.

Figure 6.8 repeats the topology and message routing table for the ring network. Table 6.5 lists the BLINK2 input parameters. Table 6.6 and Table 6.7 list the SLAM II input parameters and output values, respectively.

Ring Network

NETWORK TOPOLOGY



MESSAGE ROUTING TABLE

From Node \ To Node	1	2	3	4	5
1	--	1	1	6	6
2	10	--	2	2	10
3	9	9	--	3	3
4	4	8	8	--	4
5	5	5	7	7	--

Figure 6.8. Ring Network

Table 6.5. BLINK2 Input Parameters for the Ring Network

	LINKS 1-5	LINKS 6-10
1) Range (km)	1000	1000
2) Frequency (MHz)	50	75
3) Month	July	July
4) Hour	0400	0400
5) Transmitter Power (W)	1000	1000
6) Transmitter Gain (dBi)	10	10
7) Receiver Gain (dBi)	10	10
8) Transmitter Bit Rate (bps) . .	2000	2000
9) Probe Response Delay (sec) . .	0.02	0.02
10) Message Bits	406	406
11) Line Losses (dB)	1.00	1.00
12) System Losses (dB)	1.00	1.00
13) Receiver Noise (dB)	4.00	4.00
14) Man Made Noise Factor	1	1
15) Bit Energy to Noise (dB) . . .	9.0	9.0
16) Terrain Factor	0	0
17) Electron Line Density (el/m) .	5×10^{13}	5×10^{13}

Table 6.6. SLAM II Ring Network Input Parameters

	NODE 1	NODE 2	NODE 3	NODE 4	NODE 5
1) Message Arrival Rate (msgs/min)	10	10	10	10	10

	LINKS 1-5	LINKS 6-10
2) Trail Interarrival Rate (sec) . .	2.308	3.035
3) Trail Duration (sec)	0.949	0.542
4) Message Duration (sec)	0.210	0.210
5) Probe Response Delay (sec) . . .	0.020	0.020
6) Message Bits	406	406
7) Transmission Protocol	1	1

Table 6.7. SLAM II Ring Network Output Values

1) Transmission Time (sec)	TIME	
LINK 1		1.29
LINK 2		1.57
LINK 3		--
LINK 4		1.83
LINK 5		1.39
LINK 6		2.77
LINK 7		--
LINK 8		--
LINK 9		2.77
LINK 10		2.18
	PATH 1to3	PATH 2to5
2) Message Waiting Time (sec)	62.78	64.60
3) Throughput (bps)	61.73	62.83

The effect of frequency on transmission time is illustrated in Table 6.7. Transmission time on links 1-4 was approximately 40 percent shorter than links 6-10. However, the message waiting time and throughput for the path between nodes 1 and 3 was nearly the same as the path between nodes 2 and 5.

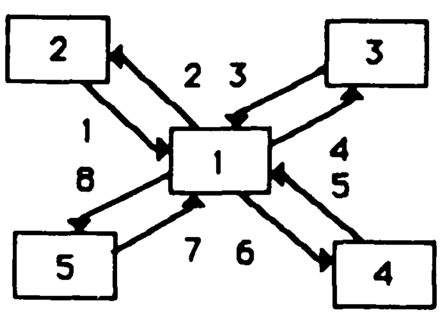
Although the path from nodes 1 and 3 uses the 50 MHz links, the performance of this path is constrained by the 75 MHz links used by messages transmitted from nodes 2 to 5. This occurred because messages from both paths must be transmitted through node 2. Messages in the transmitter buffer at node 2 using 50 MHz links must wait for messages at the front of the buffer using 75 MHz links. Transmitter frequency effects are further illustrated in Appendix C.

Star Network. The input values used in the star network were selected to demonstrate the effect of transmission protocol on MBC performance. Two antithetic and two non-antithetic simulation runs were made to generate selected output values.

Figure 6.9 repeats the topology and message routing table for the star network. Table 6.8 lists the BLINK2 input parameters. Table 6.9 lists the SLAM II input parameters, and Table 6.10 lists the SLAM II output values.

Star Network

NETWORK TOPOLOGY



MESSAGE ROUTING TABLE

To Node

From Node	1	2	3	4	5
1	--	2	4	6	8
2	1	--	1	1	1
3	3	3	--	3	3
4	5	5	5	--	5
5	7	7	7	7	--

Figure 6.9. Star Network

Table 6.8. BLINK2 Input Parameters for the Star Network

	LINKS 1-4	LINKS 5-8
1) Range (km)	1000	1000
2) Frequency (MHz)	75	75
3) Month	July	July
4) Hour	0400	0400
5) Transmitter Power (W)	1000	1000
6) Transmitter Gain (dBi)	10	10
7) Receiver Gain (dBi)	10	10
8) Transmitter Bit Rate (bps) . .	2000	2000
9) Probe Response Delay (sec) . .	0.02	0.02
10) Message Bits	1024	1024
11) Line Losses (dB)	1.00	1.00
12) System Losses (dB)	1.00	1.00
13) Receiver Noise (dB)	4.00	4.00
14) Man Made Noise Factor	1	1
15) Bit Energy to Noise (dB) . . .	9.0	9.0
16) Terrain Factor	0	0
17) Electron Line Density (el/m) .	5×10^{13}	5×10^{13}

Table 6.9. SLAM II Star Network Input Parameters

	NODE 1	NODE 2	NODE 3	NODE 4	NODE 5
1) Message Arrival Rate (msgs/min)	3	3	3	3	3

	LINKS 1-4	LINKS 5-8
2) Trail Interarrival Rate (sec) . .	2.308	2.308
3) Trail Duration (sec)	.542	.542
4) Message Duration (sec)	.519	.519
5) Probe Response Delay (sec) . . .	.020	.020
6) Message Bits	1024	1024
7) Transmission Protocol	2	1

Table 6.10. SLAM II Star Network Output Values

1) Transmission Time (sec)		TIME
LINK 1		6.26
LINK 2		6.13
LINK 3		5.97
LINK 4		6.14
LINK 5		4.35
LINK 6		4.11
LINK 7		4.35
LINK 8		4.23
	PATH 2to3	PATH 4to5
2) Message Waiting Time (sec)	108.18	108.55
3) Throughput (bps)	18.25	18.88

The effects of transmission protocol are illustrated in Table 6.10. The transmission time of links 5-8 which use protocol 1 was approximately 30 percent shorter than the transmission time of links 1-4 using protocol 2.

However, the path between nodes 2 and 3 experienced nearly the same message waiting time and throughput as the path between nodes 4 and 5. This occurred because all messages must be transmitted through node 1. Messages in the transmitter buffer at node 1 using protocol 1 links must wait for messages at the front of the buffer using protocol 2 links. The effects of transmission protocol are further demonstrated in Appendix C.

Hybrid Network. The input values used for the hybrid network were chosen to model an arbitrary PAVE PAWS network. Actual latitude and longitude coordinates of each node were

used. This model is implemented to demonstrate the feasibility of using MBC as a backup communication medium for the NORAD Attack Warning and Attack Assessment (AW/AA) network.

Figure 6.10 repeats the message routing table and Figure 6.11 repeats the topology for the first PAVE PAWS network.

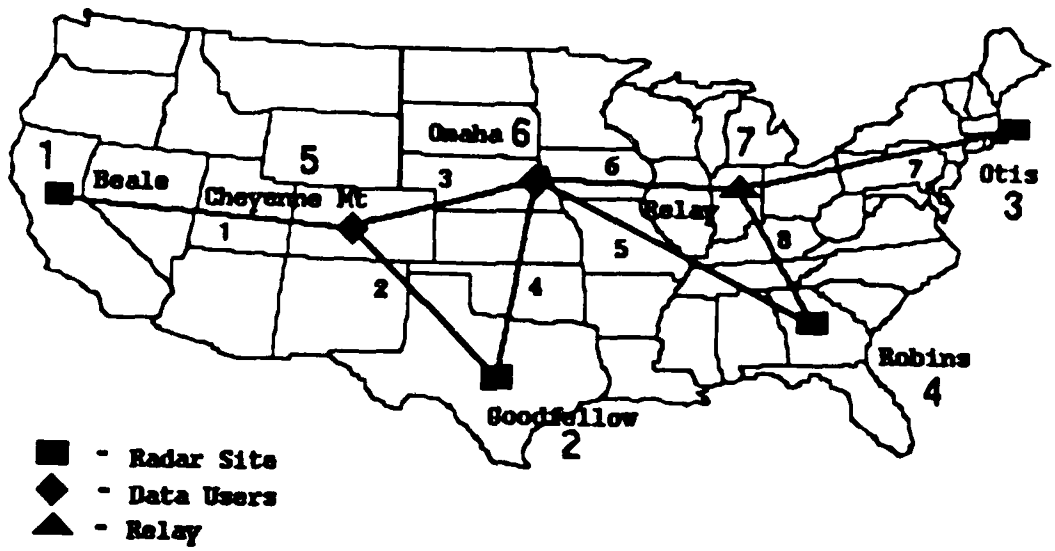
MESSAGE ROUTING TABLE

To Node

From Node	1	2	3	4	5	6	7
1	--	--	--	--	1	1	--
2	--	--	--	--	2	4	--
3	--	--	--	--	7	7	7
4	--	--	--	--	5	5	--
5	1	2	3	3	--	3	--
6	--	--	6	5	3	--	--
7	--	--	7	--	6	6	--

Figure 6.10. Message Routing Table for PAVE PAWS Network 1

PAVE PAWS Meteor Burst Network 1



Network Topology

Site	Node	Latitude	Longitude
Beale	1	39.20	121.50
Goodfellow	2	31.40	100.40
Otis	3	41.70	70.50
Robins	4	32.60	83.60
Cheyenne	5	38.80	104.80
Omaha	6	41.20	96.00
Relay	7	41.00	87.00

Total Number of Links = 8

Figure 6.11. PAVE PAWS Network 1

Table 6.11 lists the BLINK2 input parameters; Table 6.12 lists the SLAM II input parameters; and Table 6.13 lists selected SLAM II output values. Output values were generated from two antithetic and two non-antithetic simulation runs.

Table 6.11. BLINK2 Input Parameters for the First PAVE PAWS Network

	1) Range (km)	2) Frequency (MHz)
LINK 1	1440.9	30
LINK 2	914.1	40
LINK 3	794.7	50
LINK 4	1157.7	30
LINK 5	1455.9	40
LINK 6	753.6	50
LINK 7	1376.5	30
LINK 8	981.0	40

	8) Transmitter Bit Rate (bps)	10) Message Bits
NODE 1	8000	520
NODE 2	8000	520
NODE 3	8000	520
NODE 4	8000	520
NODE 5	8000	132

3) Month	May
4) Hour	1100
5) Transmitter Power (W)	1000
6) Transmitter Gain (dBi)	10
7) Receiver Gain (dBi)	10
9) Probe Response Delay (sec)	0.03
11) Line Losses (dB)	1.00
12) System Losses (dB)	1.00
13) Receiver Noise (dB)	4.00
14) Man Made Noise Factor	1
15) Bit Energy to Noise (dB)	9.0
16) Terrain Factor	0
17) Electron Line Density (el/m)	5×10^{13}

Table 6.12. SLAM II PAVE PAWS Network 1 Input Parameters

	BEALE	GOODFELLOW	OTIS	ROBINS	CHEYENNE
1) Msg Arrival Rate (msgs/min)	3	3	3	3	3
5) Probe Delay (sec)	0.03	0.03	0.03	0.03	0.03
6) Message Bits	520	520	520	520	132

	2) IA	3) BDUR	4) MDUR	7) PROTOCOL
LINK 1	15.284	0.455	0.070/0.022	2
LINK 2	12.062	0.639	0.071/0.023	2
LINK 3	14.757	0.486	0.070/0.022	2
LINK 4	9.994	0.793	0.073/0.024	2
LINK 5	18.478	0.167	0.075/0.026	2
LINK 6	15.242	0.487	0.070/0.022	2
LINK 7	13.769	0.544	0.074/0.026	2
LINK 8	11.577	0.613	0.072/0.023	2

IA - Trail Interarrival Time (sec)
BDUR - Trail Duration (sec)
MDUR - Message Duration (sec)
520 Bit Messages/132 Bit Messages

Table 6.13 lists the transmission time for each link and the message waiting time and throughput for each PAVE PAWS site - data user path. The links with the longest transmission time are links 1, 5, and 7. The decreased performance of these links is a result of range.

Link 4 is the most efficient link. The range of link 4 is close to the optimal 1000 km range, and an operating frequency of 30 MHz is used. The 30 MHz transmitter frequency is more efficient than both the 40 MHz frequency and 50 MHz frequency used ignoring ionospheric disturbances.

Table 6.13. SLAM II PAVE PAWS Network 1 Output Values

1) Transmission Time (sec)	TIME
LINK 1	10.68
LINK 2	7.96
LINK 3	9.17
LINK 4	6.12
LINK 5	16.25
LINK 6	9.18
LINK 7	9.50
2) Message Waiting Time (sec)	**TIME**
Beale to Omaha	49.88
Goodfellow to Omaha	44.13
Goodfellow to Cheyenne Mountain	22.45
Otis to Cheyenne Mountain	84.40
Robins to Cheyenne Mountain	107.50
3) Throughput	**bps**
Beale to Omaha	24.1
Goodfellow to Omaha	28.6
Goodfellow to Cheyenne Mountain	32.0
Otis to Cheyenne Mountain	24.6
Robins to Cheyenne Mountain	28.2

The longest message waiting time is experienced from Robins to Cheyenne Mountain. The poor performance of this path is a result of range and operating frequency. The next longest message waiting time was experienced from Otis to Cheyenne Mountain. This path required messages be transmitted over links 7, 6, and 3. Increased queueing delay at the nodes connecting these links would further decrease the efficiency of this path.

The shortest message waiting time was experienced from Goodfellow to Cheyenne Mountain. This path used link 4 which is the most efficient link in the network.

Little difference in throughput was produced for each of the paths. However, the greatest throughput was achieved on the Goodfellow-Cheyenne Mountain path which uses link 4. The Beale-Omaha path and the Otis-Cheyenne Mountain path experienced the worst throughput.

These results demonstrate the success of this modeling perspective. This modeling perspective can be used to predict the performance of MBC networks as a function of many complex engineering parameters and physical meteor burst properties.

VII. *Conclusions and Recommendations*

Thesis Conclusions

The ultimate objective of this thesis effort was to develop a model which can be used to evaluate any single or multiple-link MBC network. This ultimate objective was obtained by satisfying 12 sub-objectives which are described in Table 1.1.

The significant conclusions which can be drawn from this thesis effort include:

1. The MBC process can be visualized as a M/G/1 queue with server vacations.
2. Some analytical equations exist which describe this queueing behavior. However, these analytical equations are complex and are based on assumptions which limit their capability to model the MBC process.
3. Simulation can be used to effectively model the MBC process. This was demonstrated with the SLAM II network models.
4. Simulation can be validated with analytical results within the constraints of existing analytical equations.
5. After the simulation model is validated, it can be used to extend analytical results for the M/G/1 queue with server vacations.

Recommendations for Future Research

Because this thesis was focused on a high level modeling perspective, several enhancements and alternative approaches were not attempted. Several possibilities for future research are possible:

1. Extend the analytical results describing the M/G/1 queue with server vacations for the MBC scenario. Most existing results assume nonpreeptive service. However, Fuhrmann and Cooper [FuC85] claim these results can be applied to preemptive service if appropriately longer service times are used. A formula for this service time distribution could be derived. These analytical results could then be compared to the results generated by the modeling approach used in this thesis.
2. Test the SLAM II single-link module using actual meteor trail data. Middle-latitude meteor trail data is available from the Shape Technical Center. High-latitude meteor trail data is available from the RADC test link in Greenland.
3. Model the effects of overdense meteor trails with the SLAM II single-link module and determine the impact on network performance.
4. Implement adaptive routing in a SLAM II network model and compare the results to static routing.

5. Implement flood routing in a SLAM II network model and compare the results to static routing.

6. Derive a method of modeling variable bit rates and compare the results to the constant bit rate approach used in the SLAM II single-link module.

7. Implement a SLAM II network model with priority messages and compare the message waiting times to a network without priority messages.

8. Automate the creation of SLAM II network models. The automatic creation of the single-link module accomplished in this modeling perspective establishes the feasibility of this idea.

The results generated by this thesis effort and additional results which can be obtained by pursuing these recommendations will help the network designer improve the performance of MBC. Additional insight into the complexities of the M/G/1 queue with server vacations may be an further benefit. These insights will have an impact on queueing systems in general including Local Area Networks and manufacturing processes.

In closing, this research has produced a highly productive analysis tool for MBC network simulation. The modeling perspective used in this research is extendable to many operational environments. This research has also introduced a rich source of additional research issues.

Appendix A. *Glossary of Terms*

NOTATION	*DEFINITION*
ADAPTIVE ROUTING	Message routing algorithm in which a transmitter sends messages to different network nodes determined by current message traffic
AMBCS	Alaska Meteor Burst Communication System
AMBPH	The number of meteor bursts per hour long enough to transmit an entire message
AMBPM	The number of meteor bursts per minute long enough to transmit an entire message
AW/AA	NORAD Attack Warning/Attack Assessment network
BER	Bit Error Rate
BLINK	Single-link reference model developed by G. A. Marin of IBM (Burst LINK)
BLINK2	BLINK revision
BLOS	Beyond Line Of Sight
bps	Bits-Per-Second
BROADCAST TRANSMISSION	Transmission from a transmitter to multiple receivers without feedback
BURST	A MBC network simulation model developed by ITS
CSC	Computer Sciences Corporation
D-LAYER	Region of the ionosphere between 60 and 90 km
dB	Decibel
dBi	Decibel relative to an isotropic radiator
dBm	Decibel relative to a milliwatt

dBW	Decibel relative to a Watt
DCA	Defense Communications Agency
DIURNAL VARIATIONS	Meteor arrival variation caused by the earth's daily rotation
DUTY CYCLE	The ratio of meteor trail duration to meteor trail interarrival time
E-LAYER	Region of the ionosphere between 90 and 140 km
ECLIPTIC PLANE	The plane of the earth's orbit
EMP	ElectroMagnetic Pulse
F-LAYER	Region of the ionosphere between 140 and 400 km
FLOOD ROUTING	Message routing algorithm in which a transmitter sends messages to all network nodes
FOOTPRINT	The elliptical area of reception of a transmitted meteor burst signal The major axis is on the order of 3200 km, and the minor axis is on the order of 40 km.
FULL-DUPLEX LINK	MBC link which permits simultaneous transmission between two transmitters on the same meteor trail Frequencies have to be separated enough to avoid interference but close enough to utilize the same meteor trail.
GWEN	Groundwave Emergency Network
HALF-DUPLEX LINK	MBC link which only permits transmission in one direction at a time
HEMP	High-altitude ElectroMagnetic Pulse
ITS	Institute for Telecommunication Sciences
JRSC	Jam-Resistent Secure Communication

km	Kilometer
LOS	Line Of Sight
LPI/AJ	Low Probability of Intercept (LPI) and AntiJam capability (AJ)
MBC	Meteor Burst Communication
MCC	Meteor Communications Corporation
MHz	Megahertz
msec	Millisecond
NETS	National Emergency Telecommunications System
OVERDENSE METEOR TRAILS	Meter trails with more than $2x10^{14}$ electrons/meter
PAVE PAWS	Phased Array Warning System
PCA	Polar Cap Absorption
POINT-TO-POINT TRANSMISSION	Transmission from a transmitter to one receiver using feedback
PROTOCOL 1	Message piecing transmission protocol
PROTOCOL 2	Single burst message transmission protocol
RADC	Rome Air Development Center
RADC TEST LINK	RADC Thule-Sondestrom MBC link
RECEIVER DETECTION THRESHOLD	Minimum received power needed for sufficient SNR to avoid exceeding a maximum BER
RESQ	RESearch Queueing package developed by IBM
RSL	Received Signal Level
SEASONAL VARIATION	Meteor arrival variation caused by greater spatial density of meteors in summer months
SLAM II	Simulation Language for Alternative Modeling developed by A. Pritsker
SNOTEL	SNOw TELemetry meteor burst network

SNR	Signal to Noise Ratio
SPECULAR SCATTERING	VHF radio reflection from a meteor trail which is tangent to a prolate spheroid with the transmitter and receiver as foci
STATIC ROUTING	Message routing algorithm in which each transmitter delivers messages to a specific network node through the use of a routing table
UMBPH	Number of meteor bursts per hour
UMBPM	Number of meteor bursts per minute
UNDERDENSE METEOR TRAILS	Meter trails with less than 2×10^{14} electrons/meter
VHF	Very High Frequency

Appendix B. *Meteor Burst Communication Equations*

This appendix includes the equations used in BLINK2. Most equations are from BLINK. A more complete description of these equations is found in [IBM86]. Additional equations are referenced by source.

BLINK2 INPUT PARAMETERS

Fq	-	Frequency (30..120) (MHz)
Month	-	Month of the Year (1..12)
Hour	-	Hour of the Day (1..24)
P_T	-	Transmission Power (W)
G_T	-	Transmitter Antenna Gain (dB)
G_R	-	Receiver Antenna Gain (dB)
Brate	-	Transmitter Bit Rate (bps)
Pdelay	-	Probe Response Delay (msec)
Mbits	-	Number of Bits in a Message
WTREL	-	Waiting Time Reliability
L_R	-	Line Losses (W)
L_S	-	System and Line Losses (dB)
F	-	Receiver Noise Factor
N_M	-	Manmade Noise Factor
ETON	-	Bit Energy/Noise (dB)

REFERENCE LINK CONSTANTS

$UMBPH_T$	:= 60.0	- Test System Meteor Bursts/Hour
PF_T	:= 180.0	- Power Factor on Test Link (dBm)
Fq_T	:= 47.0	- Frequency on Test Link (MHz)
R_{TL}	$:= 482.8032 \cdot 10^3$	- Range from Meteor Trail to Receiver and Meteor Trail to Transmitter on the Test Link
$\sin[\phi_T]$	:= .979216	- Sine of Phi on the Test Link

PHYSICAL CONSTANTS

$Range := 1440.9 \cdot 10^{3}$ - Great Circle distance between a Transmitter and a Receiver

$R_e := 6378.388 \cdot 10^{3}$ - Radius of the earth (m)

$c := 2.997924 \cdot 10^{8}$ - Speed of Light (m/sec)

$k := 1.380662 \cdot 10^{-23}$ - Boltzman's constant (J/K)

$T_o := 290.0$ - Temperature constant (K)

$r_e := 2.8178 \cdot 10^{-15}$ - Classical Radius of the Electron (m)

$q := 5 \cdot 10^{13}$ - Electron Line Density (electrons/m)

Month and Hour Scale Factors:

$$MFCTR := \begin{array}{cl} & \text{Month} \\ \left[\begin{array}{r} .59 \\ .31 \\ .39 \\ .55 \\ 1.04 \\ 1.64 \\ 1.82 \\ 1.70 \\ 1.16 \\ 1.11 \\ 0.94 \\ 0.72 \end{array}\right] & \begin{array}{l} \text{January} \\ \text{February} \\ \text{March} \\ \text{April} \\ \text{May} \\ \text{June} \\ \text{July} \\ \text{August} \\ \text{September} \\ \text{October} \\ \text{November} \\ \text{December} \end{array} \end{array}$$

$$HFCTR := \begin{array}{cl} & \text{Hour} \\ \left[\begin{array}{r} 1.32 \\ 1.47 \\ 1.52 \\ 1.58 \\ 1.56 \\ 1.49 \\ 1.39 \\ 1.23 \\ 1.13 \\ 1.11 \\ 0.99 \\ 0.91 \\ 0.81 \\ 0.68 \\ 0.62 \\ 0.57 \\ 0.51 \\ 0.49 \\ 0.51 \\ 0.56 \\ 0.63 \\ 0.78 \\ 1.02 \\ 1.19 \end{array}\right] & \begin{array}{l} 0100 \\ 0200 \\ 0300 \\ 0400 \\ 0500 \\ 0600 \\ 0700 \\ 0800 \\ 0900 \\ 1000 \\ 1100 \\ 1200 \\ 1300 \\ 1400 \\ 1500 \\ 1600 \\ 1700 \\ 1800 \\ 1900 \\ 2000 \\ 2100 \\ 2200 \\ 2300 \\ 2400 \end{array} \end{array}$$

BLINK2 EQUATIONS

[Brw '8:24-2,24-3]

$$h := -17 \cdot \log(Fq) + 124 \tag{1}$$

$$D := 10^{(.067 \cdot h - 5.6)} \tag{2}$$

$$r_o := 10^{(.035 \cdot h - 3.45)} \tag{3}$$

where

- h - Meteor Height (Km)
- D - Ambipolar Diffusion Coefficient (m^2/sec)
- r_o - Meteor Trail Radius (m)

Convert Meteor Height from Km to m: $h := h \cdot 1000$

Calculate Power Factor (PF) [Mor85:69]

$$N_o := 10 \cdot \log\left[k \cdot T_o \cdot \left[\left[\frac{104}{L_R}\right] \cdot \left[\frac{20}{Fq}\right]^{2.3} \cdot \left[N_M\right]^2 + F\right]\right] \tag{4}$$

$$P_{TH} := N_o + 10 \cdot \log(Brate) + ETON \tag{5}$$

Assume the distance from the transmitter to the meteor trail is equal to the distance from the receiver to the meteor trail = R.

[Abe86:927]

$$R := \sqrt{\frac{Range^2}{4} + \left[h + \frac{Range^2}{8 \cdot R_e}\right]^2} \qquad (6)$$

$$R_T := R \qquad (6a)$$

$$R_R := R \qquad (6b)$$

$$\cos(\beta) := \frac{2}{\pi} \qquad \sin(\phi) := \left[1 + \left[\frac{2 \cdot h}{Range} + \frac{Range}{4 \cdot R_e}\right]^2\right]^{-.5} \qquad (7)$$

$$PFRA := 10 \cdot \log\left[\frac{R^3 \cdot \left[1 - \cos(\beta)^2 \cdot \sin(\phi)^2\right]}{R_{TL}^3 \cdot \left[1 - \cos(\beta)^2 \cdot \sin\left[\phi_T\right]^2\right]}\right] \qquad (8)$$

Convert Power and System Line Losses from Watts to dB:

$$P_T := 10 \cdot \log\left[P_T\right] \qquad L_S := 10 \cdot \log\left[L_S\right]$$

$$PF := P_T + G_T + G_R - P_{TH} - L_S - PFRA \qquad (9)$$

where

- N_o - Noise Power Spectral Density (dBW/Hz)
- P_{TH} - Receiver Detection Threshold (dBW)
- R_T - Transmitter to Meteor Trail Range (Km)
- R_R - Receiver to Meteor Trail Range (Km)
- β - Angle between the Principal Axis of the Trail and the Plane formed by R_T and R_R
- α - Angle between the electric field vector E at the Meteor Trail and R_R
- PFRA - Power Factor Range Adjustment (dB)
- PF - Power Factor (dB)

Calculate Antenna Factor (AF)

Convert Transmitter and Receiver Antenna Gain from dB to Watts:

$$G_T := 10^{\left[\frac{G_T}{10}\right]} \qquad G_R := 10^{\left[\frac{G_R}{10}\right]}$$

$$BEAMWIDTH := \begin{bmatrix} \frac{\pi}{180} \cdot \sqrt{\frac{27000}{G_R}} \\ \frac{\pi}{180} \cdot \sqrt{\frac{27000}{G_T}} \end{bmatrix} \qquad \begin{matrix} \text{Receiver Horizontal Beamwidth} \\ \text{Transmitter Horizontal Beamwidth} \end{matrix} \qquad (10)$$

$$\epsilon := \min(BEAMWIDTH) \qquad (11)$$

$$Xi := \frac{Range}{R_e} \tag{12}$$

$$X := \frac{\pi}{180} \cdot 79 \tag{13}$$

$$Psi := acos\left[\frac{R_e}{R_e + h}\right] \tag{14}$$

$$Psi := if(Psi \geq Xi, Xi, Psi) \tag{15}$$

$$S_a := \left[R_e + h\right] \cdot \left[Psi - \frac{Xi}{2}\right] - h \cdot tan\left[\frac{\pi}{2} - X\right] \tag{16}$$

$$S_b := \sqrt{R_e^2 + \left[R_e + h\right]^2 - 2 \cdot R_e \cdot \left[R_e + h\right] \cdot cos\left[\frac{Xi}{2}\right]} \cdot tan\left[\frac{\epsilon}{2}\right] \tag{17}$$

Test Link Antenna Common Area: $A_T := 394426 \cdot 10^6$ (m^2)

$$AF := \frac{\pi \cdot S_a \cdot S_b}{A_T} \tag{18}$$

where

BEAMWIDTH	- Transmitter and receiver bandwidth vector
ϵ	- Minimum transmitter or receiver bandwidth
Xi	- Angle in radians between the lines from the center of the earth to the transmitter and receiver
X	- Vertical beamwidth
Psi	- Angle in a right triangle formed by a line horizontal to the transmitter and a line from the center of the earth to a point 93 kilometers above the earth
Sa	- Semi-major axis of the transmitter/receiver common volume (km)
Sb	- Semi-minor axis of the transmitter/receiver common volume (km)
AF	- Final antenna factor adjustment

Calculate UMBPM

Convert Frequencies from MHz to Hz:

$$Fq := Fq \cdot 10^{6} \quad (Hz)$$

$$Fq_{T} := Fq_{T} \cdot 10^{6} \quad (Hz)$$

$$UMBPH := 10^{\left[\left[\frac{PF-PF_{T}}{20}\right]+1.5\cdot\log\left[\frac{Fq_{T}}{Fq}\right]\right]} \qquad (19)$$

$$UMBPH := UMBPH \cdot UMBPH_{T} \cdot AF \cdot MFCTR_{Month} \cdot HFCTR_{Hour} \qquad (20)$$

$$UMBPM := \frac{UMBPH}{60} \qquad (21)$$

where

UMBPH - Total meteor bursts per hour detected by a transmitter
UMBPM - Total meteor burst per minute detected by a transmitter

Calculate Characteristic Trail Lifetime [Mor85:28]

Compute wavelength:

$$\lambda := \frac{c}{Fq} \quad (m) \tag{22}$$

$$\sec(\phi) := \sqrt{1 + \left[\frac{Range^2}{\left[\left[2 \cdot h + \left[\frac{Range^2}{4 \cdot R_e}\right]\right]\right]^2}\right]} \tag{23}$$

$$t_c := \frac{\lambda^2 \cdot \sec(\phi)^2}{16 \cdot \pi^2 \cdot D} \tag{24}$$

where

λ - Wavelength of the transmitted radio wave
ϕ - One-half the included angle between R_T and R_R
t_c - Characteristic Meteor Trail Lifetime (sec)

Calculate Underdense Trail Duration [Mor85:16-24]

Set α and β to 90 degrees: $\alpha := \frac{\pi}{2}$ $\beta := \frac{\pi}{2}$

Convert Transmitter Power from dBW to Watts:

$$P_T := 10^{\left[\frac{P_T}{10}\right]} \quad \text{(W)}$$

Peak Power Level (W): (25)

$$P_R(t) := \frac{\left[P_T \cdot G_T \cdot G_R \cdot \lambda^3 \cdot q^2 \cdot r_e^{\,2} \cdot \sin(\alpha)^2\right] \cdot \exp\left[\frac{-8 \cdot \pi^2 \cdot \left[r_o^{\,2} + 4 \cdot D \cdot t\right]}{\lambda^2 \cdot \sec(\phi)^2}\right]}{16 \cdot \pi^2 \cdot R_T \cdot R_R \cdot \left[R_T + R_R\right] \cdot \left[1 - \cos(\beta)^2 \cdot \sin(\phi)^2\right]}$$

Convert Watts to dBW:

$$P_R(t) := 10 \cdot \log\left[P_R(t)\right] \quad \text{(dBW)}$$

$$t_u := \left[P_R(0) - P_{TH}\right] \cdot \left[\frac{t_c}{8.7}\right] \quad \text{(sec)} \qquad (26)$$

where

$P_R(t)$ - Received Carrier Power at time t (dBW)

t_u - Usable trail duration (sec)

Calculate AMBPM

$$t_0 := \frac{Pdelay}{1000} \tag{27}$$

$$MDUR := \left[\overset{(a)}{t_0} + \overset{(b)}{\frac{Mbits}{Brate}} + \overset{(c)}{2 \cdot \frac{Range}{c}} \right] \tag{28}$$

(a) - Probe response delay
(b) - Time to transmit the message
(c) - Time to transmit the first bit and last bit

$K_1 := .96 \quad K_2 := .04 \quad a_1 := 1 \quad a_2 := 10$

$$AMBPM := UMBPM \cdot \left[\underbrace{K_1 \cdot \exp\left[\frac{-\left[a_1 \cdot MDUR\right]}{t_u}\right]}_{\text{Underdense meteor trail term}} + \underbrace{K_2 \cdot \exp\left[\frac{-\left[a_2 \cdot MDUR\right]}{t_u}\right]}_{\text{Overdense meteor trail term}} \right] \tag{29}$$

where

t_0 - Probe response delay (sec)
MDUR - Total message duration (sec)
AMBPM - Number of meteor bursts per minute long enough to transmit an entire message

Calculate Message Waiting Time

$$t_{IA} := \frac{60}{UMBPM} \tag{30}$$

[Oet80:1599]

$$WTSEC1 := -t_{IA} \cdot \ln(1 - WTREL) \tag{31}$$

$$WTSEC2 := \frac{-60}{AMBPM} \cdot \ln(1 - WTREL) \tag{32}$$

where

- t_{IA} - Meteor trail interarrival time (sec)
- WTSEC1 - Message waiting time for Protocol 1 (sec)
- WTSEC2 - Message waiting time for Protocol 2 (sec)

Calculate Throughput [Mil87:148]

$$t_D := 3600$$

$$t_{XMIT} := MDUR - t_0 \tag{33}$$

$$N_{B1} := \frac{Mbits \cdot t_D}{t_{IA}} \cdot \frac{\exp\left[\dfrac{-\left[t_{XMIT} + t_0\right]}{t_u}\right]}{1 - \exp\left[\dfrac{-t_{XMIT}}{t_u}\right]} \tag{34}$$

$$N_{B2} := \frac{Mbits \cdot t_D}{t_{IA}} \cdot \exp\left[\frac{-\left[t_{XMIT} + 2 \cdot t_0\right]}{t_u}\right] \qquad (35)$$

$$TPUT_1 := \frac{N_{B1}}{t_D} \qquad (36)$$

$$TPUT_2 := \frac{N_{B2}}{t_D} \qquad (37)$$

$$TPUT_{2a} := \frac{AMBPM}{60} \cdot (Mbits) \qquad (38)$$

where

t_D - Total observation time for throughput calculation (sec)

t_{XMIT} - The time to completely transmit a message excluding the probe response delay (sec)

N_{B1} - The number of bits transmitted in time t_D using Protocol 1

N_{B2} - The number of bits transmitted in time t_D using Protocol 2

$TPUT_1$ - Protocol 1 throughput

$TPUT_2$ - Protocol 2 throughput

$TPUT_{2a}$ - Protocol 2a throughput

Calculate Optimal Bit Rate [Abe86:927]

Convert Bit Energy to Noise, Received Power, and Noise Power Spectral Density to ratio form:

$$ETON := 10^{\left[\frac{ETON}{10}\right]} \qquad \text{Bit Energy to Noise}$$

$$P_R(t) := 10^{\left[\frac{P_R(t)}{10}\right]} \qquad \text{Received Power (W)}$$

$$N_o := 10^{\left[\frac{N_o}{10}\right]} \qquad \text{Noise Power Spectral Density (W)}$$

$$t_{opt} := \frac{t_c}{2} \tag{39}$$

$$R_{opt} := \frac{P_R(0)}{e \cdot N_o \cdot ETON} \tag{40}$$

$$N_{BMAX} := \left[t_{opt} - t_0 - 2 \cdot \frac{Range}{c}\right] \cdot R_{opt} \tag{41}$$

where

- t_{opt} - meteor trail lifetime which maximizes the number of bits transmitted per trail
- R_{opt} - Transmitter bit rate which maximizes the number of bits transmitted per meteor trail
- N_{BMAX} - The number of bits transmitted per meteor trail using bit rate R_{opt}

Appendix C. *Meteor Burst Communication Performance Analysis*

This appendix includes analytical results from BLINK2. These results were chosen to demonstrate how selected engineering parameters affect MBC performance.

Table C.1. BLINK2 Input Parameters

1)	Range (m)	1000×10^3
2)	Frequency (MHz)	50
3)	Month	May
4)	Hour	1100
5)	Transmitter Power (W)	1000
6)	Transmitter Gain (dBi)	10
7)	Receiver Gain (dBi)	10
8)	Transmitter Bit Rate (bps)	2000
9)	Probe Response Delay (sec)	0.02
10)	Message Bits	406
11)	Line Losses (dB)	1.00
12)	System Losses (dB)	1.00
13)	Receiver Noise (dB)	4.00
14)	Man Made Noise Factor	1
15)	Bit Energy to Noise (dB)	9.0
16)	Terrain Factor	0
17)	Electron Line Density (el/m)	5×10^{13}

UMBPM - Unadjusted Meteor Bursts per Minute
AMBPM - Adjusted Meteor Bursts per Minute
t_u - Useable Meteor Trail Duration (sec)

P_T - Transmitter Power (W)

G_T - Transmitter Antenna Gain (dBi)

Fq - Transmitter Frequency (MHz)
Range - Great Circle Distance between a Transmitter and a Receiver
Brate - Transmitter Bit Rate (bps)

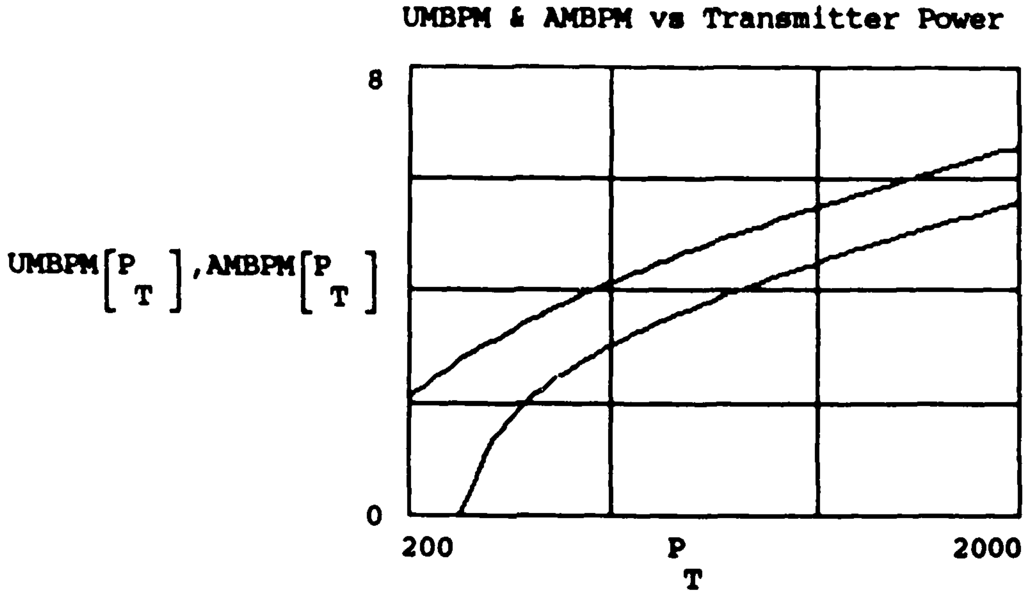


Figure C.1. Relationship between Transmitter Power, Unadjusted Meteor Bursts per Minute (UMBPM), and Adjusted Meteor Bursts per Minute (AMBPM)

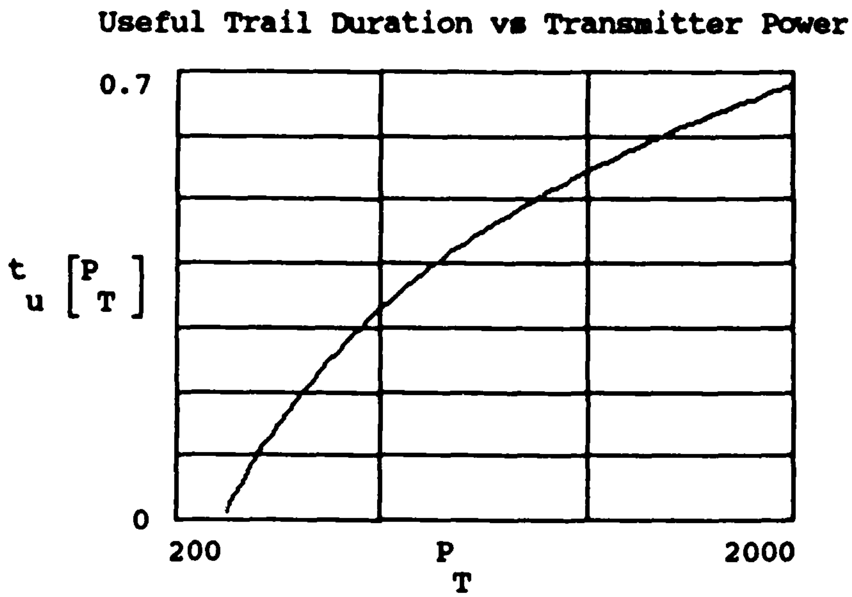


Figure C.2. Relationship between Transmitter Power and Useful Trail Duration

UMBPM & AMBPM vs Transmitter Antenna Gain

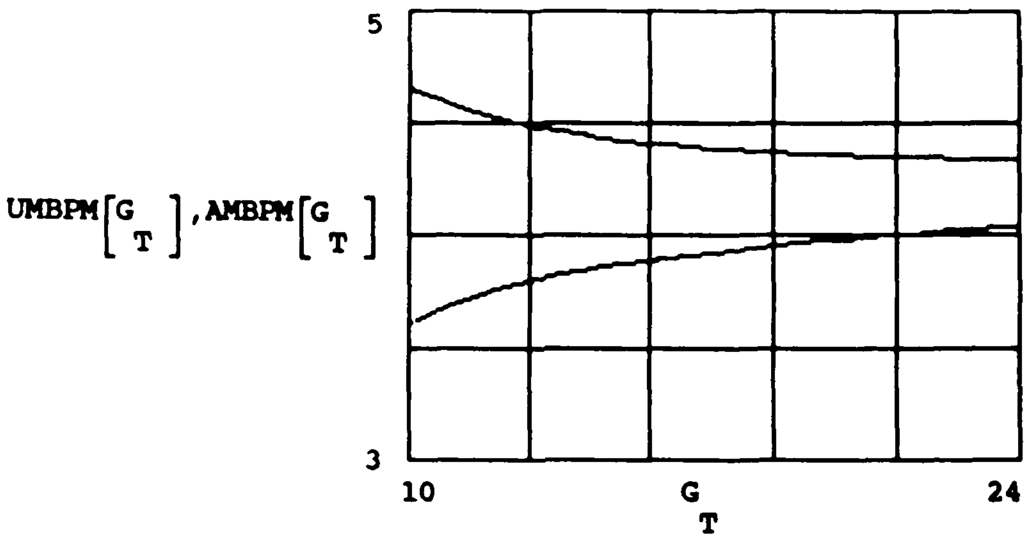


Figure C.3. Relationship between Transmitter Antenna Gain, UMBPM, and AMBPM

Useful Trail Duration vs Transmitter Antenna Gain

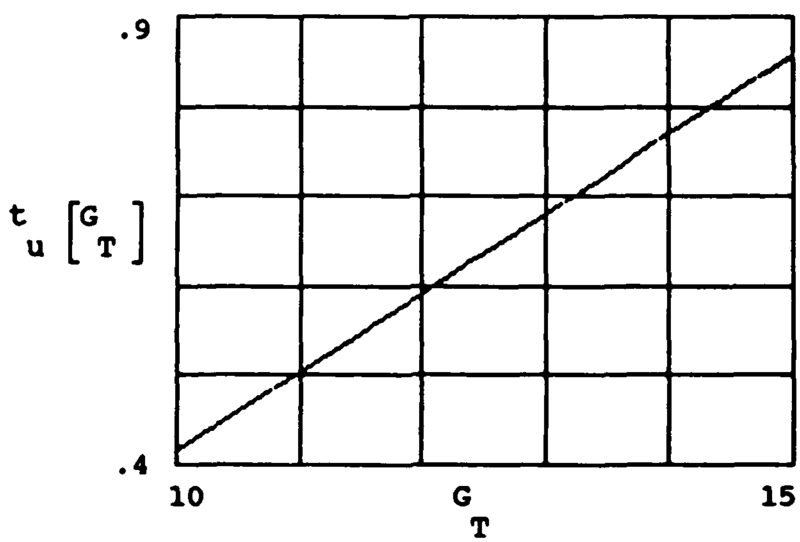


Figure C.4. Relationship between Transmitter Antenna Gain and Useful Trail Duration

UMBPM & AMBPM vs Transmitter Frequency

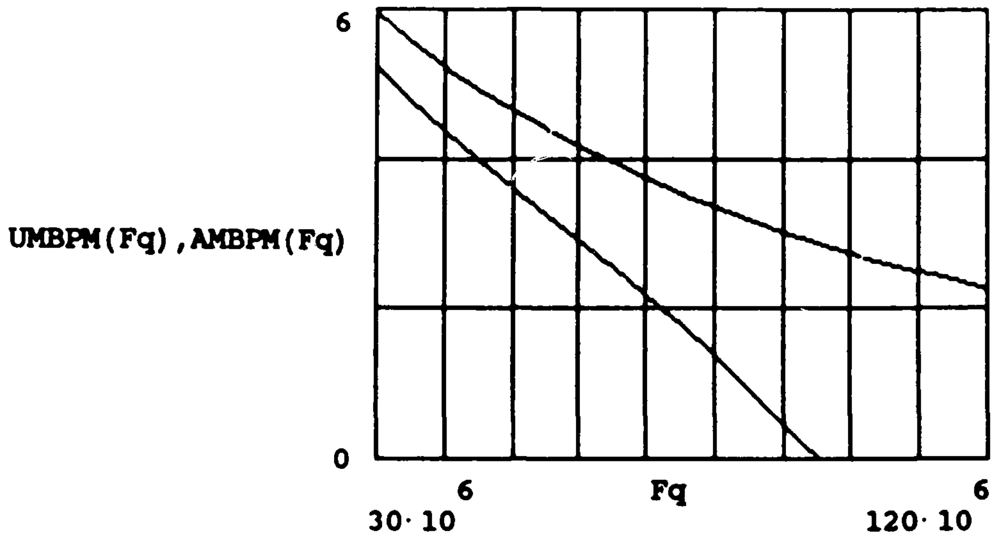


Figure C.5. Relationship between Transmitter Frequency, UMBPM, and AMBPM

Useful Trail Duration vs Transmitter Frequency

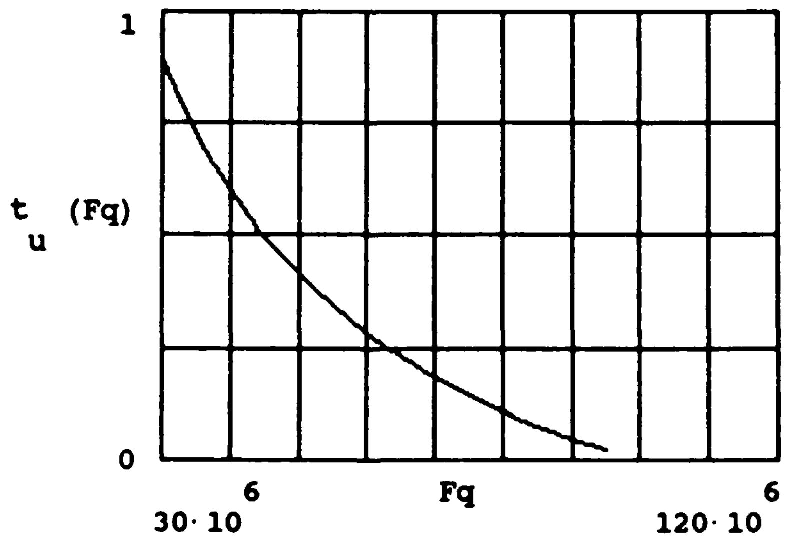


Figure C.6. Relationship between Transmitter Frequency and Useful Trail Duration

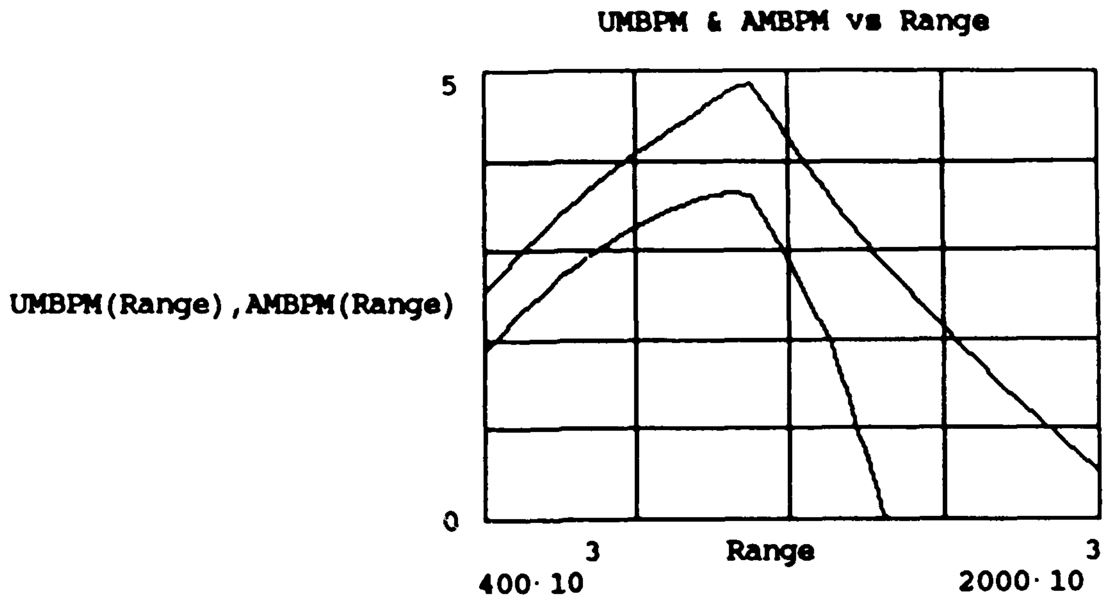


Figure C.7. Relationship between Range, UMBPM, and AMBPM

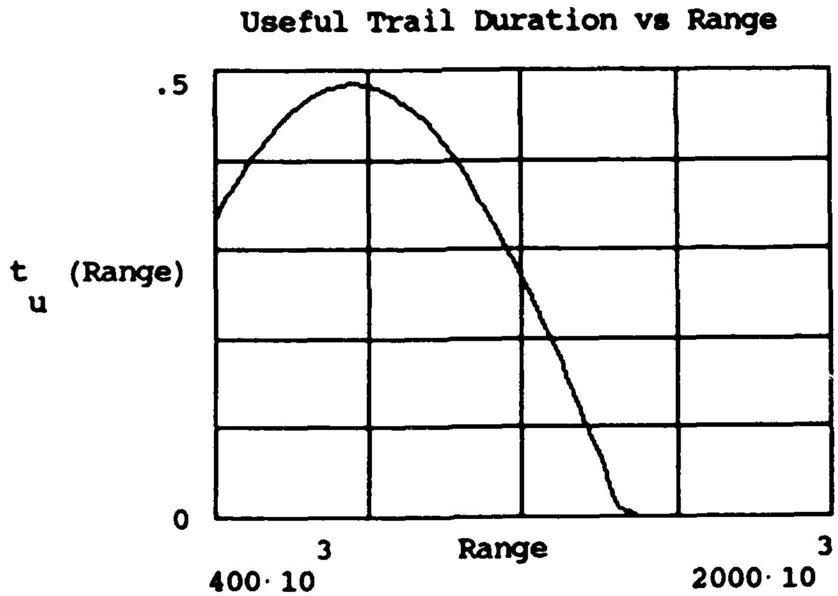


Figure C.8. Relationship between Range and Useful Trail Duration

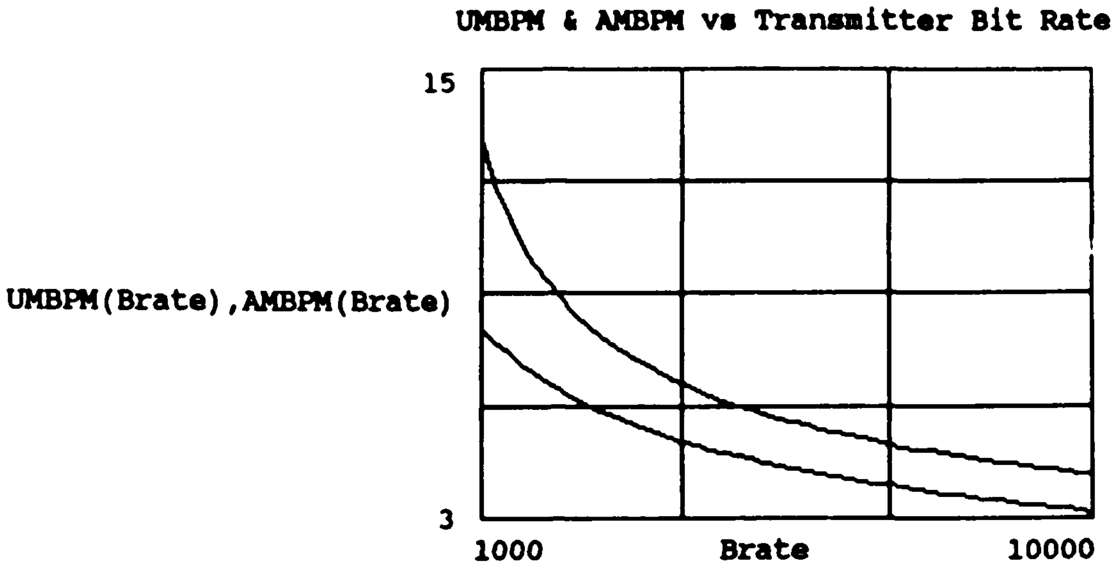


Figure C.9. Relationship between Transmitter Bit Rate, UMBPM, and AMBPM

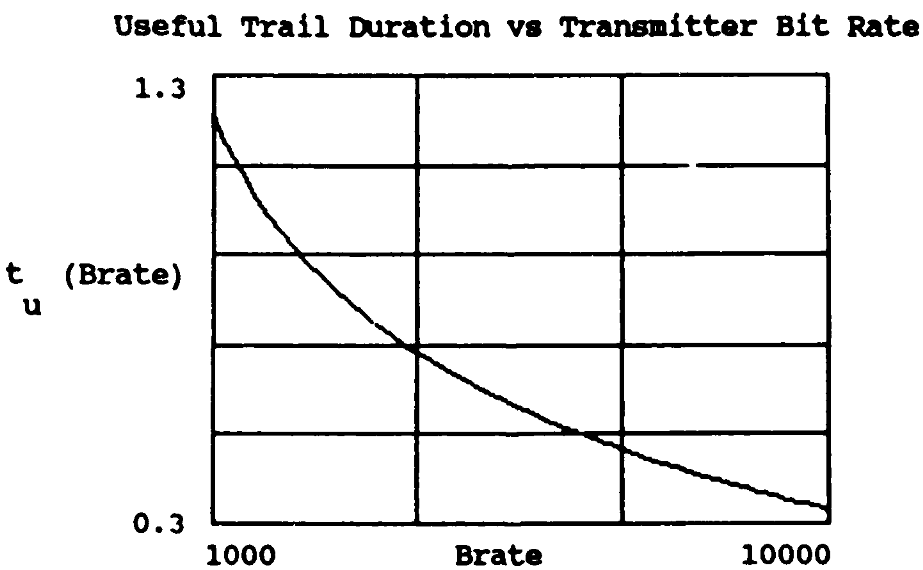


Figure C.10. Relationship between Transmitter Bit Rate and Useful Trail Duration

Appendix D. *Meteor Burst Communication Model User's Manual*

I. *System Requirements*

This software can be executed from a floppy drive or from a hard drive. A hard drive is recommended because of execution speed and is required to run SLAM II simulations. These routines can be executed on any IBM XT/AT compatible computer. A math coprocessor is not necessary but will decrease execution time. Minimum system requirements include:

- 256K of RAM,
- two double-sided floppy drives
  or
  one double-sided floppy drive and a hard drive,
- MS DOS Version 2.1 or later, and
- monochrome screen.

Optional hardware includes:
- Hercules, CGA, EGA, or VGA graphics card;
- hard drive;
- printer; and
- 8087 or 80287 math coprocessor.

Software can be obtained by contacting:

Department of Electrical and Computer Engineering
Air Force Institute of Technology
Wright-Patterson AFB OH 45433-5000
(AV) 785-3576 (COM) (513) 255-3576

II. *Installation Procedure*

A) Using floppy drives -
No installation procedure is required.
B) Using a hard drive -
Insert MBC Disk #1 in floppy drive A or B.
Type the following command:

```
INSTALL [hard drive letter] [floppy drive letter]
```

III. *Single-Link Model Execution Instructions*

The MBC single-link model is executed by using the MODEL.BAT file. This file executes the BLINK2.EXE single-link module described in Chapter 5. MODEL.BAT executes CREATE1.EXE and CREATE2.EXE which implement the SLAM II single-link module for transmission Protocols 1 and 2, respectively. MODEL.BAT also executes the following sub-modules: COPYDATA.EXE, INTRO.EXE, OUTVALS.EXE, and SLAMMSG.EXE.

STEP 1: Type MODEL
STEP 2: Type SPACECOM.DAT, MBC1.DAT, MBC2.DAT, MBC3.DAT, MBC4.DAT, MBC5.DAT, or any user created input data file when prompted for a file.
STEP 3: Type N or Y when prompted to use a nuclear data file.
STEP 4: If Y was selected, type ENVIN.DAT or any user provided nuclear data file when prompted for a file.
STEP 5: Type node numbers for desired MBC link.
STEP 6: Type Y or N to continue.
STEP 7: Type Y or N to copy the RESULT.DAT file to another file.
STEP 8: If Y was selected, type new file name for RESULT.DAT.
STEP 9: Type 1 or 2 for desired transmission protocol.
STEP 10: Enter values for -

1) Message Arrival Rate (msgs/min)
2) Meteor Trail Interarrival Time (sec)
3) Meteor Trail Duration (sec)
4) Probe Response Delay (sec)
5) Message Duration (sec)
6) Number of Message Bits
7) Random Seed #1
8) Random Seed #2

STEP 11: Type Y or N when prompted to change any parameters from step 10.
STEP 12: If Y was selected, type number of desired parameter and new value.
STEP 13: Type SYSTEM.OUT when prompted for the file name of the output data.

STEP 12: Select options: 1, 2, 4, 5, 7, or 10 from the SLAM II Report Menu.
STEP 13: Type 12 from the SLAM II Report Menu to exit.
STEP 14: Type Y or N when prompted to run another simulation.

NOTES:

1) If a graphics card is not being used, the INTRO.EXE line in the MODEL.BAT file should be removed. The following files can also be deleted:

ATT.BGI	INTRO.EXE
CGA.BGI	TRIP.CHR
EGAVGA.BGI	HERC.BGI

2) If the SLAM II single-link module is not being used, all lines after BLINK2.EXE in the MODEL.BAT file should be deleted.

3) The single-link simulation module can be executed alone by using the SLAM.BAT file. Execution consists of steps 9-14 described above.

4) Results of the last single-link simulation are contained in the file SYSTEM.OUT. This file is saved in the \MBC\SLAM subdirectory. These results can be retrieved by running \MBC\SLAM\OUTPUT.EXE and typing SYSTEM.OUT when prompted for a file name for output data.

There are two other routines provided in this software package: LATLONG.EXE and LINK.EXE. LATLONG.EXE is used to calculate the range between two sets of latitude and longitude coordinates.

LINK.EXE is used to calculate the number of possible links in a meteor burst network. This routine reads the MBC.DAT data file. LINK.EXE can be used alone or by using the LINKCALC.BAT batch file.

IV. *Network Simulation Execution Instructions*

In order to run network simulations, the PC version of SLAM II is required. Network simulations are executed by using the SLAMNET.BAT file. This procedure prompts the user for the name of the simulation file and runs the SLAM II processor. Four example network simulation files are included:

PAVEPAWS.SIM
RELAY.SIM,
RING.SIM, and
STAR.SIM.

See Chapter 5 for a description of network modeling.

V. *BLINK2 Parameter Descriptions*

BLINK2 parameters are provided by using an input data file. An example BLINK2 input data file is illustrated in Table D.1. Notes describing the format of the data fields are included at the bottom of the file.

The first parameter in the input data file is the number of nodes in the network. Following this parameter, the input data file includes node description fields. These fields include a 20 character location and the latitude and longitude coordinates for each node in the network.

The next 16 parameters are numbered 1-16. These parameters are referred to as parametric variables. The number preceding the variable is the index of the parametric variable. BLINK2 allows multiple runs specified by the 'NUMBER OF CASES' variable.

Table D.1. Sample BLINK2 Input Data File

```
10                       LAT    LONG    NUMBER OF NODES
BEALE                  39.20  121.50        NODE 1
GOODFELLOW             31.40  100.40        NODE 2
OTIS                   41.70   70.50        NODE 3
ROBINS                 32.60   83.60        NODE 4
CHEYENNE               38.80  104.80        NODE 5
OMAHA                  41.20   96.00        NODE 6
RELAY1                 41.00   87.00        NODE 7
RELAY2                 48.00  108.00        NODE 8
RELAY3                 32.00  111.00        NODE 9
RELAY4                 36.00   93.00        NODE 10
30.0            1 FREQUENCY (30..120) (MHz)
1               2 MONTH OF THE YEAR (1...12)
11              3 HOUR OF THE DAY (0...23)
1000.0          4 TRANSMISSION POWER (Watts)
10.0            5 TRANSMITTER ANTENNA GAIN (dBi)
10.0            6 RECEIVER ANTENNA GAIN (dBi)
8000            7 TRANSMITTER BIT RATE (bps)
30              8 PROBE RESPONSE DELAY (msec)
520             9 NUMBER OF BITS IN MESSAGE
0.90           10 WAITING TIME RELIABILITY LEVEL
1.0            11 LINE LOSSES (dB)
1.0            12 SYSTEM LOSSES (dB)
4.0            13 RECEIVER NOISE (dB)
1              14 MAN-MADE NOISE FACTOR
                  (1=GAL 2=QUIET 4=RURAL 10=SUB)
9.0            15 BIT ENERGY TO NOISE (dB)
5.0E13         16 ELECTRON DENSITY (el/m) [Mor85:63]
0                 TERRAIN INDEX (0,1,2,3)
                     --> INDEX*10=RMS dev from flat
3                 NUMBER OF CASES
2                 INDEX OF PARAMETRIC VARIABLE
4                 INCREMENT TO PARAMETRIC VARIABLE
```

NOTES:

1) All real numbers must have a digit before the decimal point or a run time error will occur.

2) Embedded blanks are not permitted in the node location field or a run time error will occur. Any other string upto 20 characters is permitted.

3) The first number in the data file indicates the number of nodes in the MBC network. This number must be correct or a run time error will occur.

4) The incremental value used should be a positive value.

Each run is made by incrementing the parametric variable specified by the variable, 'INDEX OF PARAMETRIC VARIABLE' by an amount specified by the variable, 'INCREMENT TO PARAMETRIC VARIABLE'. In the sample data file, three runs are specified by incrementing 'MONTH OF THE YEAR' by four. The first run is for January; the second run is for May; and the third run is for September.

Ranges for the parametric variables are provided when appropriate. The 'FREQUENCY' parametric variable is for transmitter frequency, and it ranges from 30 to 120 MHz. 'MONTH OF THE YEAR' is specified by a number from 1 to 12. 'HOUR OF THE DAY' is specified by a number from 0 to 23. 'TRANSMISSION POWER' is in Watts. Typical values range from 500 to 1000 Watts [Mor88]. 'TRANSMITTER ANTENNA GAIN' and 'RECEIVER ANTENNA GAIN' are in units of dBi. Typical values range from 10 to 24 dBi.

'TRANSMITTER BIT RATE' is in units of bps. Typical values range from 1200 bps to 256 kbps [Mor88]. Acceptable values for bit rate are a function of the other engineering parameters and the electron density of the meteor trail. Appendix B describes this relationship.

'PROBE-RESPONSE DELAY' is in units of msec. This parameter represents the probe delay between a transmitter and receiver. This parameter is a function of transmission protocol, propagation delay, synchronization, encryption,

and transmitter-receiver switching [Haa83]. Typical values range from 20 to 80 msec.

The message duration is a function of 'NUMBER OF BITS IN MESSAGE' parameter. The Adjusted Meteor Bursts Per Minute (AMBPM) decreases as the number of message bits increases. Selection of this parameter has a significant impact on Protocol 2 performance.

The 'WAITING TIME RELIABILITY LEVEL' parameter represents a confidence level from 0 to .99. This confidence level refers to the probability of successfully transmitting a message. Message waiting time results are calculated using this confidence level parameter.

The 'LINE LOSSES' parameter is in units of dB. 'LINE LOSSES' refers to the line losses between the transmitter and receiver antennas. This parameter is used to calculate the minimum received signal level (RSL). See Appendix B for equation. A typical value for 'LINE LOSSES' is 1.0 dB.

The 'SYSTEM LOSSES' parameter is in units of dB. This parameter represents other system losses in the MBC system. 'SYSTEM LOSSES' is used to calculate power factor. See Appendix B. A typical value for 'SYSTEM LOSSES' is 1.0 dB.

The 'RECEIVER NOISE' parameter is in units of dB. This parameter is a function of receiver noise figure and baseband bandwidth [Haa83]. This parameter is used to calculate the minimum RSL. See Appendix B for equation. A typical value for 'RECEIVER NOISE' is 4.0 dB.

The 'MAN-MADE NOISE FACTOR' parameter is a scale factor used in the calculation of the minimum RSL. Man-made noise is produced by electric motors, ignition systems, and power lines [Mor85]. The 'MAN-MADE NOISE FACTOR' parameter ranges from 1 to 10. This parameter refers to the level of background noise which interferes with MBC. This parameter has the following definition:

1 --> galactic noise,
2 --> quiet rural environment,
4 --> rural environment, and
10 --> suburban environment.

Any value between 1 and 10 can be selected.

The 'BIT ENERGY TO NOISE' (E/N_0) parameter is in units of dB. This parameter is used in the calculation of the minimum RSL. E/N_0 refers to the Signal to Noise Ratio (SNR) in the MBC system. A typical value for E/N_0 is 9.0 dB.

The value of the 'ELECTRON LINE DENSITY' parameter in the sample data file is provided by Morin. This is a representative value for the electron density of an underdense meteor trail. Larger values of electron density greatly improve the performance of the system. Other commonly used values for this parameter are:

- 1.00×10^{14} (electrons/meter) [Abe86] and
- 0.75×10^{14} (electrons/meter) [Sug64].

The 'TERRAIN INDEX' parameter is used by BLINK2 to determine if a LOS propagation path exists between a transmitter and a receiver. The parameter is in units of root-mean-square (RMS) deviation/10.0 from flat terrain.

This parameter is an integer number and can take on the values of 0, 1, 2, or 3.

For a more detailed description of these parameters the following sources can be consulted [IBM86], [IBM85], [Mor85], and [Haa83].

VI. *Single-Link Model Output*

The single-link model output consists of analytical results produced by BLINK2 and simulation results produced by the single-link simulation module. BLINK2 creates two output files. The first is OUTVALS.DAT, and the other is RESULT.DAT. OUTVALS.DAT is used to display Protocol 1 and Protocol 2 parameters to simulate with the single-link module. RESULTS.DAT is a complete summary of all the BLINK2 results. The equations used to generate these results are included in Appendix B. A copy of the RESULTS.DAT output file is included in Appendix G.

The single-link simulation module output consists of mean values and histograms for:

message buffer size,
message buffer delay,
message transmission time, and
message waiting time.

Message buffer delay is the time a message waits in the buffer until it begins transmission. Message transmission time is the time required to transmit a message. Message waiting time is the total time a message spends in the system which includes buffer delay and transmission time.

Mean values are provided for trails per message and throughput.

VII. *Network Simulation Model Output*

The network simulation output consists of the message arrival rate for each node, transmission time per link, and message waiting time and throughput for multiple link paths. Histograms are provided for transmission time and message waiting time. Appendix H includes network simulation results.

VIII. *File Descriptions*

A) SCREEN CONTROL FILES:

```
ATT.BGI     - AT&T screen device driver
CGA.BGI     - CGA/MCGA screen device driver
EGAVGA.BGI  - EGA/VGA screen device driver
HERC.BGI    - Hercules screen device driver
TRIP.CHR    - Triplex font file
```

B) DATA FILES:

```
ENVIN.DAT     - Nuclear environment parameters data
                file. (Optional)
LINK.DAT      - Output file created by LINKCALC.EXE.
MBC.DAT       - BLINK2.EXE input data file.
MBC1.DAT      - Alternate BLINK2.EXE input data file.
MBC2.DAT      - Alternate BLINK2.EXE input data file.
MBC3.DAT      - Alternate BLINK2.EXE input data file.
MBC4.DAT      - Alternate BLINK2.EXE input data file.
MBC5.DAT      - Alternate BLINK2.EXE input data file.
OUTVALS.DAT   - Output file used to display BLINK2.EXE
                results for simulation input.
RESULT.DAT    - Text output file created by BLINK2.EXE.
SPACECOM.DAT  - Space Command/LKXP meteor burst
                parameter data file.
SYSTEM.DAT    - Temporary file used for the SLAM II
                processor.
XVALS.DAT     - Propagation data for terrain
                conditions, ranges, and frequencies.
                See BLINK USERS MANUAL.
```

C) EXECUTABLE FILES:

BLINK2.EXE	-	Main routine. Calculates all single link meteor burst results.
COPYDATA.EXE	-	Copies data files to MBC.DAT for use by BLINK2.EXE.
COPYSIM.EXE	-	Copies a network simulation file to file SYSTEM.DAT.
CREATE1.EXE	-	Prompts the user for simulation input values for Protocol 1 transmission, creates the SLAM II single-link module code, and copies the code to file SYSTEM.DAT.
CREATE2.EXE	-	Prompts the user for simulation input values for Protocol 2 transmission, creates the SLAM II single-link module code, and copies the code to file SYSTEM.DAT.
EXECUTIO.EXE	-	SLAM II execution processor.
INPUT.EXE	-	SLAM II code translator.
INTRO.EXE	-	Screen routine which displays network introduction.
LATLONG.EXE	-	Calculates the range between two points given the latitude and longitude coordinates.
LINK.EXE	-	Calculates the maximum number of Meteor Burst Communication links from MBC.DAT.
OUTPUT.EXE	-	SLAM II output processor.
OUTVALS.EXE	-	Displays the OUTVALS.DAT file created by BLINK2.EXE.
QUESTION.EXE	-	Utility program used to provide interactive batch files.
README.COM	-	Utility program used to display the README file.
SLAMMSG.EXE	-	Screen routine to indicate the beginning of a simulation run.

D) BATCH FILES:

INSTALL.BAT	-	Installation procedure.
INSTALL2.BAT	-	Continuation of the installation procedure.
LINKCALC.BAT	-	Executes COPYDATA.EXE and LINK.EXE.
MODEL.BAT	-	Executes COPYDATA.EXE, NETWORK.EXE, and BLINK2.EXE.
SLAM.BAT	-	Executes CREATE1.EXE or CREATE2.EXE and runs the SLAM II simulation processor.
SLAMNET.BAT	-	Executes COPYSIM.EXE and runs the SLAM II simulation processor.

E) SIMULATION FILES:

E.FIX	-	Command file used for EXECUTIO.EXE.
I.FIX	-	Command file used for INPUT.EXE.
PAVEPAWS.SIM	-	PAVE PAWS network simulation file.
PAVEPAWS.SUM	-	Execution summary produced by PAVEPAWS.SIM
RELAY.SIM	-	Relay network simulation file.
RELAY.SUM	-	Execution summary produced by RELAY.SIM.
RING.SIM	-	Ring network simulation file.
RING.SUM	-	Execution summary produced by RING.SIM.
SLAM33.LIB	-	SLAM II library (Student PC version)
SLAM32.LIB	-	SLAM II library (PC version)
STAR.SIM	-	Star network simulation file.
STAR.SUM	-	Execution summary produced by STAR.SIM.
SYSTEM.OUT	-	Output file created by OUTPUT.EXE

Appendix E. *Slam II Single-Link Module Source Code*

This appendix includes the SLAM II code for the single-link module using transmission Protocols 1 and 2. The single-link module includes a message transmission process and a meteor trail arrival process. Figure E.1 describes the message transmission process, and Figure E.2 describes the meteor trail arrival process.

This appendix also includes the code to implement Protocol 2a. An example is also provided to illustrate how overdense meteor trails can be modeled.

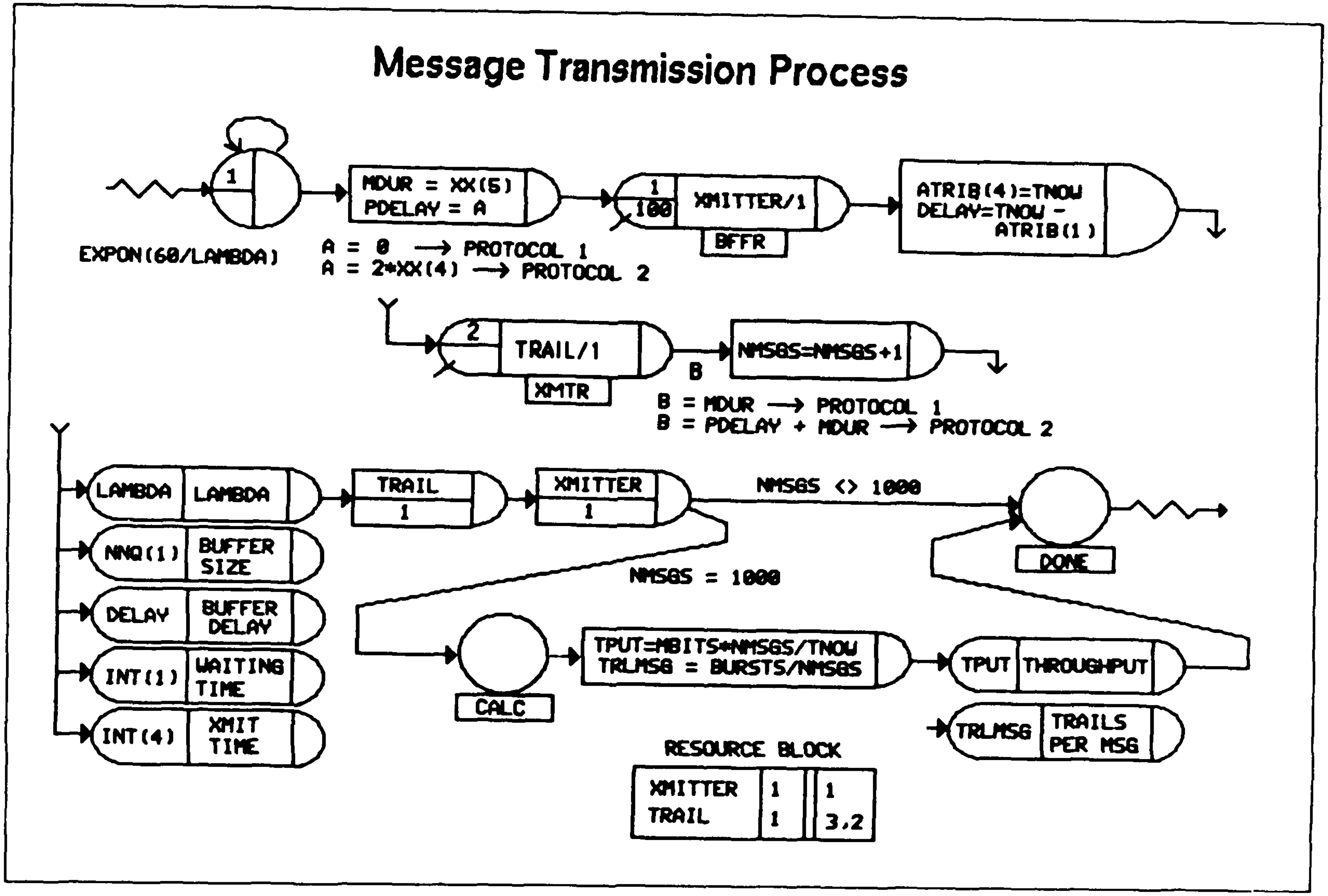


Figure E.1. Message Transmission Process

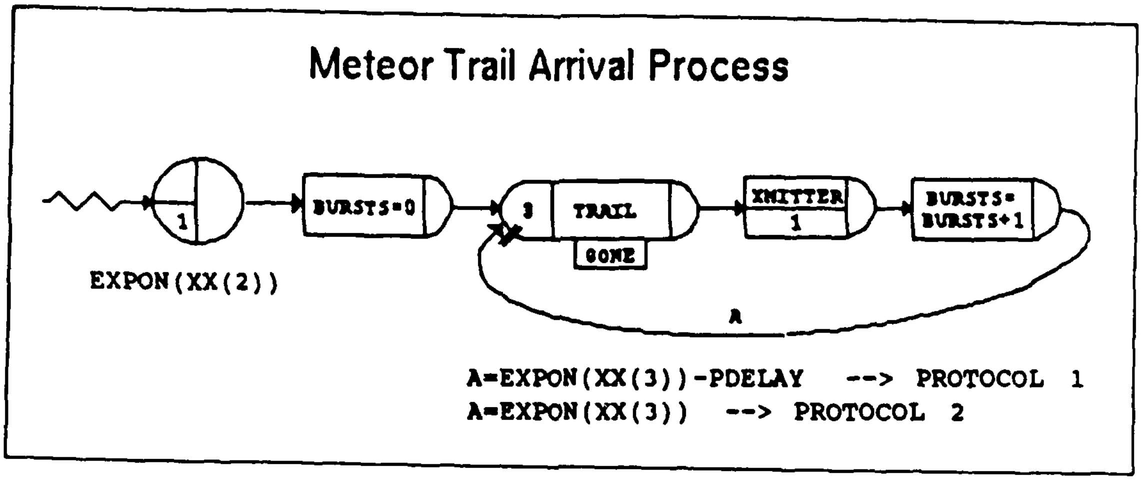


Figure E.2. Meteor Trail Arrival Process

```
GEN,HEALY,MBC PROTOCOL 1,09/19/88,1,,NO,,NO;
LIMITS,3,5,105;
;
;            PROTOCOL 1 - MESSAGE PIECING MESSAGE TRANSFER
;
SEEDS,535(1),-87686(2);
INTLC,XX(1)=12,XX(2)=30,XX(3)=.5,XX(4)=.02,XX(5)=.3,XX(6)=520;
;   XX(1) --> LAMBDA, mean message arrival rate --> (lambda msgs/min)
;   XX(2) --> IA,     mean meteor burst interarrival time (sec)
;   XX(3) --> BDUR,   mean meteor burst duration (mu)     (sec)
;   XX(4) --> PDELAY, probe response delay  (sec)
;   XX(5) --> MDUR,   message duration  (sec)
;   XX(6) --> MBITS,  number of bits in a message
;
;   XX(7) --> DELAY,  time xmit begins - message arrival time (sec)
;   XX(8) --> BURSTS, the number of trails used for msg xmit
;   XX(9) --> NMSGS,  message counter
;   XX(10)--> TPUT,   average throughput  (bps)
;   ATRIB(1) -->          message arrival time
;   ATRIB(2) --> PDELAY,  probe response delay  (sec)
;   ATRIB(3) --> MDUR,    message duration  (sec)
;   ATRIB(4) -->          time message begins transmission
;   ATRIB(5) --> NBAR,    trail counter for message transfer
;
      EQUIVALENCE/XX(1),LAMBDA/
                  XX(2),IA/
                  XX(3),BDUR/
                  XX(4),PDELAY/
                  XX(6),MBITS/
                  XX(7),DELAY/
                  XX(8),BURSTS/
                  XX(9),NMSGS/
                  XX(10),TPUT/
```

```
                 ATRIB(3),MDUR/
                 ATRIB(5),NBAR;
NETWORK;
      RESOURCE/XMITTER(1),1;        use entities from file1
      RESOURCE/TRAIL(1),3,2;        use entities from file3 then file2
;
      ASSIGN,NMSGS=0;               initialize the message counter
;
;
;
;-------------- Message Transmission Process -------------------
;
      CREATE,EXPON(60/LAMBDA),,1;   create messages
      ASSIGN,MDUR=XX(5);            message transmission time
;
;
;           [  message buffer will hold 100 messages  ]
;           [  additional messages are discarded      ]
;
BFFR  AWAIT(1/100),XMITTER/1,BALK(OVFL);   wait for transmitter
      ASSIGN,NBAR=0;                       initialize trail count
      ASSIGN,ATRIB(4)=TNOW;         time message begins transmission
      ASSIGN,DELAY=TNOW-ATRIB(1);   calculate buffer delay
;
XMTR  AWAIT(2),TRAIL/1;             wait for meteor arrival
      ASSIGN,NBAR=NBAR+1;           increment trail count
      ACT/1,MDUR;                   MSG XMIT
;
;
      ASSIGN,BURSTS=NBAR;           record number of required bursts
      ASSIGN,NMSGS=NMSGS+1;         increment the message counter
      COLCT,LAMBDA,LAMBDA min;                message arrival rate
      COLCT,NNQ(1),BUFFER SIZE,10/0/10;       buffer size histogram
      COLCT,DELAY,BUFFER DELAY sec,20/0/10;   buffer delay histogram
      COLCT,INT(1),WAITING TIME sec,20/0/10;  time in system histogram
      COLCT,INT(4),XMIT TIME sec,20/0/2;      transmit time histogram
      COLCT,BURSTS,TRAILS PER MSG,9/1/1;      trails/msg histogram
;
      FREE,TRAIL/1;                  message is done with meteor trail
      FREE,XMITTER/1;                free transmitter for next message
;
      ACT,,NMSGS.EQ.1000,CALC;       calculate tput after 1000 msgs
      ACT,,NMSGS.NE.1000,DONE;       NMSGS < 1000
CALC  GOON,1;
      ASSIGN,TPUT=MBITS*NMSGS/TNOW;  throughput = total bits/total time
      COLCT,TPUT,THROUGHPUT bps;     record tput
DONE  TERM,1000;                     terminate after 1000 msgs
;
;
OVFL  COLCT,BET,TIME BET. BALKS;     time between message overflows
      TERM,10;                       terminate after 10 balks
;
;
```

```
;
;-------------- Meteor Trail Arrival Process --------------------
;
       CREATE,,.300,,1;                      wait for the first meteor burst
GONE   PREEMPT(3),TRAIL,XMTR,3;              remaining xmit time --> XMIT
       ACT/2,EXPON(XX(2),1);                        BURST INT
       FREE,TRAIL/1;                                METEOR TRAIL ARRIVAL
       ACT/3,EXPON(XX(3),2)-PDELAY,,GONE;           BURST DUR
       ENDNETWORK;
INIT;
FIN;
```

```
GEN,HEALY,MBC PROTOCOL 2,09/19/88,1,,NO,,NO;
LIMITS,3,6,105;
;
;              PROTOCOL 2 - SINGLE BURST MESSAGE TRANSFER
;
SEEDS,53(1),-6466(2);
INTLC,XX(1)=12,XX(2)=25,XX(3)=.5,XX(4)=.02,XX(5)=.2,XX(6)=250;
;    XX(1) --> LAMBDA, mean message arrival rate --> (lambda msgs/min)
;    XX(2) --> IA,     mean meteor burst interarrival time (sec)
;    XX(3) --> BDUR,   mean meteor burst duration (mu)     (sec)
;    XX(4) --> PDELAY, probe response delay  (sec)
;    XX(5) --> MDUR,   message duration time (sec)
;    XX(6) --> MBITS,  number of bits in a message
;
;    XX(7) --> DELAY,  time xmit begins - message arrival time (sec)
;    XX(8) --> BURSTS, the number of trails used for msg xmit
;    XX(9) --> NMSGS,  message counter
;    XX(10)--> TPUT,   average throughput (bps)
;    ATRIB(1) -->         message arrival time
;    ATRIB(2) --> PDELAY, probe response delay  (sec)
;    ATRIB(3) --> MDUR,   message duration time (sec)
;    ATRIB(4) -->         time message begins transmission
;    ATRIB(5) --> NBAR,   trail counter for message transfer
;    ATRIB(6) -->         remaining xmit time after trail <NOT USED>
;
      EQUIVALENCE/XX(1),LAMBDA/
                  XX(2),IA/
                  XX(3),BDUR/
                  XX(6),MBITS/
                  XX(7),DELAY/
                  XX(8),BURSTS/
                  XX(9),NMSGS/
                  XX(10),TPUT/
                  ATRIB(2),PDELAY/
                  ATRIB(3),MDUR/
                  ATRIB(5),NBAR;
NETWORK;
      RESOURCE/XMITTER(1),1;        use entities from file1
      RESOURCE/TRAIL(1),3,2;        use entities from file3 then file2
;
      ASSIGN,NMSGS=0;               initialize the message counter
;
;
;
;-------------- Message Transmission Process --------------------
;
      CREATE,EXPON(60/LAMBDA),,1;           create messages
      ASSIGN,PDELAY=2*XX(4);                probe response delay
      ASSIGN,MDUR=XX(5);                    message duration
;
;
```

```
;           [  message buffer will hold 100 messages  ]
;           [  additional messages are discarded       ]
;
BFFR  AWAIT(1/100),XMITTER/1,BALK(OVFL);   wait for transmitter
      ASSIGN,NBAR=0;                     initialize trail count
      ASSIGN,ATRIB(4)=TNOW;              time message begins transmission
      ASSIGN,DELAY=TNOW-ATRIB(1);        calculate buffer delay
;
XMTR  AWAIT(2),TRAIL/1;                  wait for meteor arrival
      ASSIGN,NBAR=NBAR+1;                increment trail count
      ACT/1,PDELAY+MDUR;                 MSG XMIT
;
;
      ASSIGN,BURSTS=NBAR;                record number of required bursts
      ASSIGN,NMSGS=NMSGS+1;              increment the message counter
      COLCT,LAMBDA,LAMBDA min;           message arrival rate
      COLCT,NNQ(1),BUFFER SIZE,10/0/10;          buffer size histogram
      COLCT,DELAY,BUFFER DELAY sec,20/0/25;      buffer delay histogram
      COLCT,INT(1),WAITING TIME sec,20/0/25;     time in system histogram
      COLCT,INT(4),XMIT TIME sec,10/0/5;         transmit time histogram
      COLCT,BURSTS,TRAILS PER MSG,9/1/1;         trails/msg histogram
;
      FREE,TRAIL/1;                      message is done with meteor trail
      FREE,XMITTER/1;                    free transmitter for next message
;
      ACT,,NMSGS.EQ.1000,CALC;           calculate tput after 1000 msgs
      ACT,,NMSGS.NE.1000,DONE;           NMSGS < 1000
CALC  GOON,1;
      ASSIGN,TPUT=MBITS*NMSGS/TNOW;  throughput = total bits/total time
      COLCT,TPUT,THROUGHPUT bps;     record tput
DONE  TERM,1000;                     terminate after 1000 msgs
;
;
OVFL  COLCT,BET,TIME BET. BALKS;     time between message overflows
      TERM,10;                       terminate after 10 balks
;
;
;
;-------------- Meteor Trail Arrival Process -------------------
;
      CREATE,,.300,,1;                   wait for the first meteor burst
GONE  PREEMPT(3),TRAIL,XMTR,6;           remaining xmit time --> NOT USED
      ACT/2,EXPON(XX(2),1);              BURST INT
      FREE,TRAIL/1;                      METEOR TRAIL ARRIVAL
      ACT/3,EXPON(XX(3),2),,GONE;        BURST DUR
      END;
INIT;
FIN;
```

```
GEN,HEALY,MBC PROTOCOL 2a,09/19/88,1,,NO,,NO;
LIMITS,3,6,105;
;
;                 PROTOCOL 2a - SINGLE BURST MESSAGE TRANSFER
;
;SEEDS,123456789(1),999789(2);
;SEEDS,-123456789(1),-999789(2);
;SEEDS,77475(1),813455(2);
SEEDS,-77475(1),-813455(2);
INTLC,XX(1)=2.75,XX(2)=15.266,XX(3)=0.45,XX(4)=.03,XX(5)=.138,XX(6)=1024
;
;   XX(1) ==> LAMBDA, mean message arrival rate --> (lambda msgs/min)
;   XX(2) ==> IA,     mean meteor burst interarrival time (sec)
;   XX(3) ==> BDUR,   mean meteor burst duration (mu)     (sec)
;   XX(4) ==> PDELAY, probe response delay  (sec)
;   XX(5) ==> MDUR,   message duration (sec)
;   XX(6) ==> MBITS,  number of bits in a message
;
;   XX(7) ==> DELAY,  time xmit begins - message arrival time (sec)
;   XX(8) ==> BURSTS, the number of trails used for msg xmit
;   XX(9) ==> NMSGS,  message counter
;   XX(10)==> TPUT,   average throughput (bps)
;   XX(11)==> NXTR,   the amount of time after the completion of one
;                     message and the beginning of the next message
;                     (sec)
;   ATRIB(1) ==>         message arrival time
;   ATRIB(2) ==> PDELAY, probe response delay  (sec)
;   ATRIB(3) ==> MDUR,   message transmission time (sec)
;   ATRIB(4) ==>         time message begins transmission
;   ATRIB(5) ==> NBAR,   trail counter for message transfer
;
      EQUIVALENCE/XX(1),LAMBDA/
                  XX(2),IA/
                  XX(3),BDUR/
                  XX(6),MBITS/
                  XX(7),DELAY/
                  XX(8),BURSTS/
                  XX(9),NMSGS/
                  XX(10),TPUT/
                  XX(11),NXTR/
                  ATRIB(2),PDELAY/
                  ATRIB(3),MDUR/
                  ATRIB(5),NBAR;
NETWORK;
      RESOURCE/XMITTER(1),1;         use entities from file1
      RESOURCE/TRAIL(1),3,2;         use entities from file3 then file2
;
      ASSIGN,NMSGS=0;                initialize the message counter
;
;
;
```

```
;-------------- Message Transmission Process -------------------
;
     CREATE,EXPON(60/LAMBDA),,1;      create messages
     ASSIGN,PDELAY=2*XX(4);           probe response delay
     ASSIGN,MDUR=XX(5);               message transmission time
;
;
;         [  message buffer will hold 100 messages  ]
;         [  additional messages are discarded      ]
;
BFFR AWAIT(1/100),XMITTER/1,BALK(OVFL);   wait for transmitter
     ASSIGN,NBAR=0;                       initialize trail count
     ASSIGN,ATRIB(4)=TNOW;                begin transmission
     ASSIGN,DELAY=TNOW-ATRIB(1);          calculate buffer delay
;
;
XMTR AWAIT(2),TRAIL/1;                    wait for meteor arrival
     ASSIGN,NBAR=NBAR+1;                  increment trail count
     ACT/1,PDELAY+MDUR;                   MSG XMIT
;
;
;      [ 50% of the time additional waiting time composed of the  ]
;      [ remainder of the trail and interarrival time is incurred ]
;
     FREE,TRAIL/1;               message is done with meteor trail
     ASSIGN,NXTR=EXPON(IA)+EXPON(BDUR)-PDELAY-MDUR;
     ACT,NXTR,.5,CONT;
     ACT,,.5,CONT;
;
;
CONT GOON,1;
     ASSIGN,BURSTS=NBAR;                     record bursts
     ASSIGN,NMSGS=NMSGS+1;                   message counter
     COLCT,LAMBDA,MSGS PER MIN;              record message arrival rate
     COLCT,NNQ(1),BUFFER SIZE,10/0/10;       buffer size histogram
     COLCT,DELAY,BUFFER DELAY,20/0/25;       buffer delay histogram
     COLCT,INT(1),MSG WAITING TIME,20/0/25;  TIS histogram
     COLCT,INT(4),TRANSMIT TIME,10/0/5;      transmit time histogram
     COLCT,BURSTS,TRAILS PER MSG,9/1/1;      trails/msg histogram
;
     FREE,XMITTER/1;                         free transmitter
;
     ACT,,NMSGS.EQ.1000,CALC;                calculate throughput
     ACT,,NMSGS.NE.1000,DONE;                NMSGS <= 1000
CALC GOON,1;
     ASSIGN,TPUT=MBITS*NMSGS/TNOW;       tput = total bits/total time
     COLCT,TPUT,THROUGHPUT BPS;          record tput
DONE TERM,1000;                          terminate after 1000 msgs
;
;
OVFL COLCT,BET,TIME BET. BALKS;          time between msg overflows
     TERM,10;                            terminate after 10 balks
;
```

```
;
;
;--------------- Meteor Trail Arrival Process --------------------
;
      CREATE,,.300,,1;                wait for the first meteor burst
GONE  PREEMPT(3),TRAIL,XMTR,6;        end trail, remaining xmit time -->
NOT USED
      ACT/2,EXPON(XX(2),1);           BURST INT
      FREE,TRAIL/1;                   METEOR TRAIL ARRIVAL
      ACT/3,EXPON(XX(3),2),,GONE;     BURST DUR
      END;
INIT;
FIN;
```

```
GEN,HEALY,MBC PROTOCOL 1,09/19/88,1,,NO,,NO;
LIMITS,3,5,105;
;
;              PROTOCOL 1 - MESSAGE PIECING MESSAGE TRANSFER
;                           WITH UNDERDENSE AND OVERDENSE METEOR TRAILS
;
SEEDS,42343(1),543453(2);
INTLC,XX(1)=15,XX(2)=15.266,XX(3)=1.50,XX(4)=.45;
INTLC,XX(5)=.03,XX(6)=.075,XX(7)=520;
;   XX(1) --> LAMBDA, mean message arrival rate --> (lambda msgs/min)
;   XX(2) --> IA,     mean meteor trail interarrival time (sec)
;   XX(3) --> OVRDUR, mean overdense meteor trail duration (sec)
;   XX(4) --> UNDDUR, mean underdense meteor trail duration (sec)
;   XX(5) --> PDELAY, probe response delay  (sec)
;   XX(6) --> MDUR,   message duration  (sec)
;   XX(7) --> MBITS,  number of bits in a message
;
;   XX(8) --> DELAY,  time xmit begins - message arrival time (sec)
;   XX(9) --> BURSTS, the number of trails used for msg xmit
;   XX(10)--> NMSGS,  message counter
;   XX(11)--> TPUT,   average throughput  (bps)
;   XX(12)--> TRLMSG, trails per message
;   ATRIB(1) -->         message arrival time
;   ATRIB(2) --> PDELAY, probe response delay  (sec)
;   ATRIB(3) --> MDUR,   message duration  (sec)
;   ATRIB(4) -->         time message begins transmission
;
      EQUIVALENCE/XX(1),LAMBDA/
                  XX(2),IA/
                  XX(3),OVRDUR/
                  XX(4),UNDDUR/
                  XX(5),PDELAY/
                  XX(7),MBITS/
                  XX(8),DELAY/
                  XX(9),BURSTS/
                  XX(10),NMSGS/
                  XX(11),TPUT/
                  XX(12),TRLMSG/
                  ATRIB(3),MDUR;
NETWORK;
      RESOURCE/XMITTER(1),1;      use entities from file1
      RESOURCE/TRAIL(1),3,2;      use entities from file3 and file2
;
;
;
;--------------- Message Transmission Process --------------------
;
      CREATE,EXPON(60/LAMBDA),,1;          create messages
      ASSIGN,MDUR=XX(6);                   message transmission time
;
;
;            [  message buffer will hold 100 messages  ]
;            [  additional messages are discarded      ]
```

```
;
BFFR  AWAIT(1/100),XMITTER/1,BALK(OVFL);     wait for transmitter
      ASSIGN,ATRIB(4)=TNOW;                  begin transmission
      ASSIGN,DELAY=TNOW-ATRIB(1);            calculate buffer delay
;
XMTR  AWAIT(2),TRAIL/1;                      wait for meteor arrival
      ACT/1,MDUR;                            MSG XMIT
;
;
      ASSIGN,NMSGS=NMSGS+1;                  increment the message counter
      COLCT,LAMBDA,LAMBDA min;               message arrival rate
      COLCT,NNQ(1),BUFFER SIZE,10/0/10;      buffer size histogram
      COLCT,DELAY,BUFFER DELAY sec,20/0/10;  buffer delay histogram
      COLCT,INT(1),WAITING TIME sec,20/0/10; TIS histogram
      COLCT,INT(4),XMIT TIME sec,20/0/2;     transmit time histogram
;
      FREE,TRAIL/1;                          done with meteor trail
      FREE,XMITTER/1;                        free transmitter
;
      ACT,,NMSGS.EQ.1000,CALC;               calc tput after 1000 msgs
      ACT,,NMSGS.NE.1000,DONE;               NMSGS < 1000
CALC  GOON,1;
      ASSIGN,TPUT=MBITS*NMSGS/TNOW;          tput = total bits/total time
      ASSIGN,TRLMSG=BURSTS/NMSGS;            calculate trails/msg
      COLCT,TRLMSG,TRAILS PER MSG;
      COLCT,TPUT,THROUGHPUT bps;             record tput
DONE  TERM,1000;                             terminate after 1000 msgs
;
;
OVFL  COLCT,BET,TIME BET. BALKS;             time between msg overflows
      TERM,10;                               terminate after 10 balks
;
;
;
;--------------- Meteor Trail Arrival Process --------------------
;
      CREATE,,,,1;                           start with no trail
      ASSIGN,BURSTS=0;                       initialize trail counter
GONE  PREEMPT(3),TRAIL,XMTR,3;               remaining time --> XMIT
      ACT/2,EXPON(IA);                       TRAIL IA
      FREE,TRAIL/1;                          meteor trail arrival
      ASSIGN,BURSTS=BURSTS+1;                increment trail count
      ACT,,.1,OVDN;                          10% overdense trail
      ACT,,.9,UNDN;                          90% underdense trail
OVDN  GOON,1;
      ACT/3,EXPON(OVRDUR)-PDELAY,,GONE;      OVDN DUR
UNDN  GOON,1;
      ACT/4,EXPON(UNDDUR)-PDELAY,,GONE;      UNDN DUR

      ENDNETWORK;
INIT;
FIN;
```

Appendix F. *PAVE PAWS Network Source Code*

This appendix includes the SLAM II source code for the 7-node PAVEPAWS Hybrid network.

```
GEN,HEALY,PAVEPAWS MBC NETWORK,09/14/88,1,,NO,,NO;
LIMITS,25,14,400;
;SEEDS,1234567(1),4367651(2),6121137(3),884345(4);
;SEEDS,6733(5),450259(6),22981693(7),4882719(8);
;SEEDS,-1234567(1),-4367651(2),-6121137(3),-884345(4);
;SEEDS,-6733(5),-450259(6),-22981693(7),-4882719(8);
;SEEDS,7777777(1),4343441(2),6333337(3),765435(4);
;SEEDS,6443(5),456565(6),22444423(7),5588779(8);
SEEDS,-7777777(1),-4343441(2),-6333337(3),-765435(4);
SEEDS,-6443(5),-456565(6),-22444423(7),-5588779(8);
;
      EQUIVALENCE/ATRIB(1),WTSEC/
                  ATRIB(2),XBAR/
                  ATRIB(3),SRC/
                  ATRIB(4),DEST/
                  ATRIB(5),INDEX/
                  ATRIB(6),LINK/
                  ATRIB(7),MDUR/
                  ATRIB(8),MBITS/
                  ATRIB(9),TPUT/
                  ATRIB(10),PDELAY/
                  ATRIB(11),BRATE/
                  ATRIB(12),RANGE/
                  ATRIB(13),ORIGIN;
;
      EQUIVALENCE/XX(45),NMSGS1/
                  XX(46),NMSGS2/
                  XX(47),NMSGS3/
                  XX(48),NMSGS4/
                  XX(49),NMSGS5/
                  XX(50),NNODES;
;
;   ATRIB(1)  --> WTSEC,  total Time in System  (sec)
;   ATRIB(2)  --> XBAR,   mean message transmission time  (sec)
;   ATRIB(3)  --> SRC,    current message transmitter node
;   ATRIB(4)  --> DEST,   final message receiver node
;   ATRIB(5)  --> INDEX,  index for link range and probe delay tables
;   ATRIB(6)  --> LINK,   current link for message transmission
;   ATRIB(7)  --> MDUR,   message duration for the current link  (sec)
;   ATRIB(8)  --> MBITS,  number of bits in a message
;   ATRIB(9)  --> TPUT,   throughput calculated for each message
;   ATRIB(10) --> PDELAY, probe response delay  (sec)
```

```
;   ATRIB(11) ==> BRATE,  burst data rate at a transmitter  (bps)
;   ATRIB(12) ==> RANGE,  great circle range between nodes  (Km)
;   ATRIB(13) ==> ORIGIN, the original transmitter node
;   XX(45)    ==> NMSGS1, # msgs to CHEYENNE from GOODFELLOW
;   XX(46)    ==> NMSGS2, # msgs to CHEYENNE from OTIS
;   XX(47)    ==> NMSGS3, # msgs to CHEYENNE from ROBINS
;   XX(48)    ==> NMSGS4, # msgs to OMAHA from BEALE
;   XX(49)    ==> NMSGS5, # msgs to OMAHA from GOODFELLOW
;   XX(50)    ==> NNODES, number of nodes in the network
;
;
INTLC,XX(50)=7;          7 - NODE NETWORK
;
;         LAMBDA - mean message arrival rate --> (lambda msgs/min)
;
;          LAMBDA
INTLC,    XX(1)=3.00;   NODE1 --> BEALE
INTLC,    XX(2)=3.00;   NODE2  -> GOODFELLOW
INTLC,    XX(3)=3.00;   NODE3 --> OTIS
INTLC,    XX(4)=3.00;   NODE4 --> ROBINS
INTLC,    XX(5)=.100;   NODE5 --> CHEYENNE MOUNTAIN
;
;
;--------------- Construct Message Routing Table -----------------
;
      ARRAY(1,7)/0, 0, 0, 0, 1, 1, 0;
      ARRAY(2,7)/0, 0, 0, 0, 2, 4, 0;
      ARRAY(3,7)/0, 0, 0, 0, 7, 7, 7;
      ARRAY(4,7)/0, 0, 0, 0, 5, 5, 0;
      ARRAY(5,7)/1, 2, 3, 3, 0, 3, 0;
      ARRAY(6,7)/0, 0, 6, 5, 3, 0, 0;
      ARRAY(7,7)/0, 0, 7, 0, 6, 6, 0;
;
;
;------------------- Construct Link Range Table ------------------
;                       and Probe Delay Table
;
;                         NETWORK LINKS
;         All Links use Protocol 2 Message Transmission
;
;
;                          Link Range Table
;
      ARRAY(8,7) /     0,     0,     0,     0,1440.9,1440.9,     0;
      ARRAY(9,7) /     0,     0,     0,     0, 914.1,1157.7,     0;
      ARRAY(10,7)/     0,     0,     0,     0,1376.5,1376.5,1376.5;
      ARRAY(11,7)/     0,     0,     0,     0,1455.9,1455.9,     0;
      ARRAY(12,7)/1440.9, 914.1, 794.7, 794.7,     0, 794.7,     0;
      ARRAY(13,7)/     0,     0, 753.6,1455.9, 794.7,     0,     0;
      ARRAY(14,7)/     0,     0,1376.5,     0, 753.6, 753.6,     0;
;
;
```

```
;                          Probe Delay Table
;                   <Initialized to 0 for Protocol 1>
;                 <Initialized to PDELAY for Protocol 2>
;
      ARRAY(15,7)/  0,    0,    0,    0, .03, .03,   0;
      ARRAY(16,7)/  0,    0,    0,    0, .03, .03,   0;
      ARRAY(17,7)/  0,    0,    0,    0, .03, .03, .03;
      ARRAY(18,7)/  0,    0,    0,    0, .03, .03,   0;
      ARRAY(19,7)/.03,  .03,  .03,  .03,   0, .03,   0;
      ARRAY(20,7)/  0,    0,  .03,  .03, .03,   0,   0;
      ARRAY(21,7)/  0,    0,  .03,    0, .03, .03,   0;
;
;
;
;----------  1)  Initialize Meteor Trail Interarrival  -----------
;                Times and Durations for each Link
;            2)  Initialize Probe Response Delay for
;                each Link for Protocol 1.  <Set to 0 for Protocol 2>
;
;        IA            BDUR          PDELAY
INTLC,XX(51)=15.284,  XX(52)=.455,  XX(53)=0;   LINK 1
INTLC,XX(54)=12.062,  XX(55)=.639,  XX(56)=0;   LINK 2
INTLC,XX(57)=14.757,  XX(58)=.486,  XX(59)=0;   LINK 3
INTLC,XX(60)= 9.994,  XX(61)=.793,  XX(62)=0;   LINK 4
INTLC,XX(63)=18.478,  XX(64)=.167,  XX(65)=0;   LINK 5
INTLC,XX(66)=15.242,  XX(67)=.487,  XX(68)=0;   LINK 6
INTLC,XX(69)=13.769,  XX(70)=.544,  XX(71)=0;   LINK 7
INTLC,XX(72)=11.577,  XX(73)=.613,  XX(74)=0;   LINK 8
;
;
NETWORK;
      RESOURCE/XMITTER1(1),10;          BEALE transmitter resource
      RESOURCE/XMITTER2(1),11,12;       GOODFELLOW transmitter resource
      RESOURCE/XMITTER3(1),13;          OTIS transmitter resource
      RESOURCE/XMITTER4(1),14;          ROBINS transmitter resource
      RESOURCE/XMITTER5(1),15;          CHEYENNE 5 transmitter resource
      RESOURCE/XMITTER6(1),16;          OMAHA transmitter resource
      RESOURCE/XMITTER7(1),17;          RELAY transmitter resource
      RESOURCE/TRAIL1(1),18,1;          LINK 1 trail resource
      RESOURCE/TRAIL2(1),19,2;          LINK 2 trail resource
      RESOURCE/TRAIL3(1),20,3;          LINK 3 trail resource
      RESOURCE/TRAIL4(1),21,4;          LINK 4 trail resource
      RESOURCE/TRAIL5(1),22,5;          LINK 5 trail resource
      RESOURCE/TRAIL6(1),23,6;          LINK 6 trail resource
      RESOURCE/TRAIL7(1),24,7;          LINK 7 trail resource
      RESOURCE/TRAIL8(1),25,8;          LINK 8 trail resource
;
      ASSIGN,NMSGS1=0;                  initialize the number of msgs
      ASSIGN,NMSGS2=0;                  initialize the number of msgs
      ASSIGN,NMSGS3=0;                  initialize the number of msgs
      ASSIGN,NMSGS4=0;                  initialize the number of msgs
      ASSIGN,NMSGS5=0;                  initialize the number of msgs
;
```

```
;
;------------------- Message Creation Process -------------------
;
;           NODE1 - BEALE
      CREATE,EXPON(60/XX(1)),,1;        BEALE --> message creations
      COLCT,XX(1),BEALE mps;            Record the message arrival rate
      ASSIGN,ORIGIN=1;                  Original node is BEALE
      ASSIGN,SRC=1;                     Source node is BEALE
      ASSIGN,DEST=6;                    Destination node is OMAHA
      ASSIGN,MBITS=520;                 520 bits/message
      ASSIGN,BRATE=8000;                Burst data rate = 8000 bps
      ACT,,,XMIT;                       Route message to a transmitter
;
;           NODE2 - GOODFELLOW
      CREATE,EXPON(60/XX(2)),,1;        GOODFELLOW --> message creations
      COLCT,XX(2),GOODFELLOW mps;       Record the message arrival rate
      ASSIGN,ORIGIN=2;                  Original node is GOODFELLOW
      ASSIGN,SRC=2;                     Source node is GOODFELLOW
      ASSIGN,MBITS=520;                 520 bits/message
      ASSIGN,BRATE=8000;                Burst data rate = 8000 bps
      GOON,2;
        ACT,,,CHEY;
        ACT,,,OMAH;
CHEY  ASSIGN,DEST=5;                    Destination node is CHEYENNE
      ACT,,,XMIT;                       Route message to a transmitter
OMAH  ASSIGN,DEST=6;                    Destination node is OMAHA
      ACT,,,XMIT;                       Route message to a transmitter
;
;           NODE3 - OTIS
      CREATE,EXPON(60/XX(3)),,1;        OTIS --> message creations
      COLCT,XX(3),OTIS mps;             Record the message arrival rate
      ASSIGN,ORIGIN=3;                  Original node is OTIS
      ASSIGN,SRC=3;                     Source node is OTIS
      ASSIGN,DEST=5;                    Destination node is CHEYENNE
      ASSIGN,MBITS=520;                 520 bits/message
      ASSIGN,BRATE=8000;                Burst data rate = 8000 bps
      ACT,,,XMIT;                       Route message to a transmitter
;
;           NODE4 - ROBINS
      CREATE,EXPON(60/XX(4)),,1;        ROBINS --> message creations
      COLCT,XX(4),ROBINS mps;           Record the message arrival rate
      ASSIGN,ORIGIN=4;                  Original node is ROBINS
      ASSIGN,SRC=4;                     Source node is ROBINS
      ASSIGN,DEST=5;                    Destination node is CHEYENNE
      ASSIGN,MBITS=520;                 520 bits/message
      ASSIGN,BRATE=8000;                Burst data rate = 8000 bps
      ACT,,,XMIT;                       Route message to a transmitter
;
;           NODE5 - CHEYENNE MOUNTAIN
      CREATE,600,,1;                    CHEYENNE --> message creations
      COLCT,XX(5),CHEYENNE mps;         Record the message arrival rate
      ASSIGN,ORIGIN=5;                  Original node is CHEYENNE
      ASSIGN,SRC=5;                     Source node is CHEYENNE
```

```
      ASSIGN,MBITS=132;                   132 bits/message
      ASSIGN,BRATE=8000;                  Burst data rate = 8000 bps
      GOON,4;
         ACT,,,BEAL;                      Send messages to BEALE
         ACT,,,GOOD;                                       GOODFELLOW
         ACT,,,OTIS;                                       OTIS
         ACT,,,ROBI;                                       ROBINS
BEAL  ASSIGN,DEST=1;                      Destination node is BEALE
      ACT,,,XMIT;                         Route message to a transmitter
GOOD  ASSIGN,DEST=2;                      Destination node is GOODFELLOW
      ACT,,,XMIT;                         Route message to a transmitter
OTIS  ASSIGN,DEST=3;                      Destination node is OTIS
      ACT,,,XMIT;                         Route message to a transmitter
ROBI  ASSIGN,DEST=4;                      Destination node is ROBINS
      ACT,,,XMIT;                         Route message to a transmitter
;
;
;----------------- Message Transmission Process -----------------
;
XMIT  GOON,1;
      ASSIGN,LINK=ARRAY(SRC,DEST);        link is calculated from current
      ASSIGN,INDEX=SRC+NNODES;            and final nodes
      ASSIGN,RANGE=ARRAY(INDEX,DEST);           assign link range
      ASSIGN,MDUR=MBITS/BRATE+2*RANGE/299792;   calc message duration
      ASSIGN,INDEX=INDEX+NNODES;          assign probe delay
      ASSIGN,PDELAY=ARRAY(INDEX,DEST);    <0 for protocol 1>
      ACT,,SRC.EQ.1,BFF1;                 message is at BEALE
      ACT,,SRC.EQ.2,BFF2;                 message is at GOODFELLOW
      ACT,,SRC.EQ.3,BFF3;                 message is at OTIS
      ACT,,SRC.EQ.4,BFF4;                 message is at ROBINS
      ACT,,SRC.EQ.5,BFF5;                 message is at CHEYENNE MOUNTAIN
      ACT,,SRC.EQ.6,BFF6;                 message is at OMAHA
      ACT,,SRC.EQ.7,BFF7;                 message is at RELAY
;
;
;           [  BEALE, GOODFELLOW, OTIS, and ROBINS      ]
;           [  message buffers will hold  50 messages   ]
;           [  CHEYENNE MOUNTAIN and OMAHA              ]
;           [  message buffers will hold 100 messages   ]
;           [  additional messages are discarded        ]
;
BFF1  AWAIT(10/50),XMITTER1/1,BALK(OVFL);  BEALE message buffer
      ASSIGN,XBAR=TNOW;                   message receives transmitter
XMB1  AWAIT(1),TRAIL1/1;                  message waits for trail
      ACT/1,PDELAY+MDUR;                  LINK 1 XMIT
      FREE,TRAIL1/1;                      free the trail
      ASSIGN,XBAR=TNOW-XBAR;              calculate transmission time
      COLCT,XBAR,LINK 1 XBAR,15/0/3;      transmission time histogram
      FREE,XMITTER1/1;                    free the transmitter
      ACT,,,NEXT;                         determine next link

BFF2  GOON,1;
      ACT,,DEST.EQ.5,BF2A;                use Buffer 2A for CHEYENNE
```

```
      ACT,,DEST.EQ.6,BF2B;                   use Buffer 2B for OMAHA
BF2A  AWAIT(11/50),XMITTER2/1,BALK(OVFL);  GOODFELLOW to CHEYENNE buffer
      ASSIGN,XBAR=TNOW;                      message receives transmitter
XMG2  AWAIT(2),TRAIL2/1;                     message waits for trail
      ACT/2,PDELAY+MDUR;                     LINK 2 XMIT
      FREE,TRAIL2/1;                         free the trail
      ASSIGN,XBAR=TNOW-XBAR;                 calculate transmission time
      COLCT,XBAR,LINK 2 XBAR,15/0/3;         transmission time histogram
      FREE,XMITTER2/1;                       free the transmitter
      ACT,,,NEXT;                            determine next link
BF2B  AWAIT(12/50),XMITTER2/1,BALK(OVFL);  GOODFELLOW to OMAHA buffer
      ASSIGN,XBAR=TNOW;                      message receives transmitter
XMG4  AWAIT(4),TRAIL4/1;                     message waits for trail
      ACT/4,PDELAY+MDUR;                     LINK 4 XMIT
      FREE,TRAIL4/1;                         free the trail
      ASSIGN,XBAR=TNOW-XBAR;                 calculate transmission time
      COLCT,XBAR,LINK 4 XBAR,15/0/3;         transmission time histogram
      FREE,XMITTER2/1;                       free the transmitter
      ACT,,,NEXT;                            determine next link
;
BFF3  AWAIT(13/50),XMITTER3/1,BALK(OVFL);  OTIS message buffer
      ASSIGN,XBAR=TNOW;                      message receives transmitter
XMO7  AWAIT(7),TRAIL7/1;                     message waits for trail
      ACT/7,PDELAY+MDUR;                     LINK 7 XMIT
      FREE,TRAIL7/1;                         free the trail
      ASSIGN,XBAR=TNOW-XBAR;                 calculate transmission time
      COLCT,XBAR,LINK 7 XBAR,15/0/3;         transmission time histogram
      FREE,XMITTER3/1;                       free the transmitter
      ACT,,,NEXT;                            determine next link
;
BFF4  AWAIT(14/50),XMITTER4/1,BALK(OVFL);  ROBINS message buffer
      ASSIGN,XBAR=TNOW;                      message receives transmitter
XMR5  AWAIT(5),TRAIL5/1;                     message waits for trail
      ACT/5,PDELAY+MDUR;                     LINK 5 XMIT
      FREE,TRAIL5/1;                         free the trail
      ASSIGN,XBAR=TNOW-XBAR;                 calculate transmission time
      COLCT,XBAR,LINK 5 XBAR,15/0/3;         transmission time histogram
      FREE,XMITTER4/1;                       free the transmitter
      ACT,,,NEXT;                            determine next link
;
BFF5  AWAIT(15/100),XMITTER5/1,BALK(OVFL);  CHEYENNE message buffer
      ASSIGN,XBAR=TNOW;                      message receives transmitter
      ACT,,DEST.EQ.1,XMC1;                   use LINK 1 for BEALE
      ACT,,DEST.EQ.2,XMC2;                   use LINK 2 for GOODFELLOW
      ACT,,DEST.EQ.3,XMC3;                   use LINK 3 for OTIS
      ACT,,DEST.EQ.4,XMC3;                   use LINK 3 for ROBINS
      ACT,,DEST.EQ.6,XMC3;                   use LINK 3 for OMAHA
XMC1  AWAIT(1),TRAIL1/1;                     messages waits for trail
      ACT/1,PDELAY+MDUR;                     LINK 1 XMIT
      FREE,TRAIL1/1;                         free the trail
      ASSIGN,XBAR=TNOW-XBAR;                 calculate transmission time
;     COLCT,XBAR,CHEY BEALE XBAR,15/0/3;     transmission time histogram
      FREE,XMITTER5/1;                       free the transmitter
```

```
         ACT,,,NEXT;                         determine next link
XMC2     AWAIT(2),TRAIL2/1;                  message waits for trail
         ACT/2,PDELAY+MDUR;                  LINK 2 XMIT
         FREE,TRAIL2/1;                      free the trail
         ASSIGN,XBAR=TNOW-XBAR;              calculate transmission time
;        COLCT,XBAR,CHEY GDFLW XBAR,15/0/3;     transmission time histogram
         FREE,XMITTER5/1;                    free the transmitter
         ACT,,,NEXT;                         determine next link
XMC3     AWAIT(3),TRAIL3/1;                  message waits for trail
         ACT/3,PDELAY+MDUR;                  LINK 3 XMJT
         FREE,TRAIL3/1;                      free the trail
         ASSIGN,XBAR=TNOW-XBAR;              calculate transmission time
            ACT,,ORIGIN.EQ.1,N16;            record BEALE messages to OMAHA
            ACT,,ORIGIN.EQ.5,N56;            record CHEYENNE messages to OMAHA
N16      COLCT,XBAR,LINK 3 XBAR,15/0/3;      transmission time histogram
            ACT,,,CONT;
;N56      COLCT,XBAR,CHEY OMAHA XBAR,15/0/3;     transmission time histogram
N56      GOON,1;
            ACT,,,CONT;
CONT     FREE,XMITTER5/1;                    free the transmitter
         ACT,,,NEXT;                         determine next link
;
BFF6     AWAIT(16/100),XMITTER6/1,BALK(OVFL);  OMAHA message buffer
         ASSIGN,XBAR=TNOW;                   message receives transmitter
         ACT,,DEST.EQ.5,XOM3;                use LINK 3 for CHEYENNE MOUNTAIN
         ACT,,DEST.EQ.4,XOM5;                use LINK 5 for ROBINS
         ACT,,DEST.EQ.3,XOM6;                use LINK 6 for OTIS
XOM3     AWAIT(3),TRAIL3/1;                  message waits for trail
         ACT/3,PDELAY+MDUR;                  LINK 3 XMIT
         FREE,TRAIL3/1;                      free the trail
         ASSIGN,XBAR=TNOW-XBAR;              calculate transmission time
;        COLCT,XBAR,LINK 3 XBAR,15/0/3;      transmission time histogram
         FREE,XMITTER6/1;                    free the transmitter
         ACT,,,NEXT;                         determine next link
XOM5     AWAIT(5),TRAIL5/1;                  message waits for trail
         ACT/5,PDELAY+MDUR;                  LINK 5 XMIT
         FREE,TRAIL5/1;                      free the trail
         ASSIGN,XBAR=TNOW-XBAR;              calculate transmission time
;        COLCT,XBAR,OMAHA ROBIN XBAR,15/0/3;    transmission time histogram
         FREE,XMITTER6/1;                    free the transmitter
         ACT,,,NEXT;                         determine next link
XOM6     AWAIT(6),TRAIL6/1;                  message waits for trail
         ACT/6,PDELAY+MDUR;                  LINK 6 XMIT
         FREE,TRAIL6/1;                      free the trail
         ASSIGN,XBAR=TNOW-XBAR;              calculate transmission time
;        COLCT,XBAR,OMAHA RELAY XBAR,15/0/3;    transmission time histogram
         FREE,XMITTER6/1;                    free the transmitter
         ACT,,,NEXT;                         determine next link
;
BFF7     AWAIT(17/50),XMITTER7/1,BALK(OVFL);  RELAY message buffer
         ASSIGN,XBAR=TNOW;                   message receives transmitter
         ACT,,DEST.EQ.5,XMR6;                use LINK 6 for CHEYENNE MOUNTAIN
         ACT,,DEST.EQ.3,XMR7;                use LINK 7 for OTIS
```

```
XMR6  AWAIT(6),TRAIL6/1;                  message waits for trail
      ACT/6,PDELAY+MDUR;                  LINK 6 XMIT
      FREE,TRAIL6/1;                      free the trail
      ASSIGN,XBAR=TNOW-XBAR;              calculate transmission time
      COLCT,XBAR,LINK 6 XBAR,15/0/3;      transmission time histogram
      FREE,XMITTER7/1;                    free the transmitter
      ACT,,,NEXT;                         determine next link
XMR7  AWAIT(7),TRAIL7/1;                  message waits for trail
      ACT/7,PDELAY+MDUR;                  LINK 7 XMIT
      FREE,TRAIL7/1;                      free the trail
      ASSIGN,XBAR=TNOW-XBAR;              calculate transmission time
;     COLCT,XBAR,RELAY OTIS XBAR,15/0/3;    transmission time histogram
      FREE,XMITTER7/1;                    free the transmitter
      ACT,,,NEXT;                         determine next link
;
;
;---------------- Determine the Next NODE ----------------------
;
NEXT  GOON,1;
      ACT,,LINK.EQ.1 .AND. SRC.EQ.5,ND1;
      ACT,,LINK.EQ.1 .AND. SRC.EQ.1,ND5;
      ACT,,LINK.EQ.2 .AND. SRC.EQ.5,ND2;
      ACT,,LINK.EQ.2 .AND. SRC.EQ.2,ND5;
      ACT,,LINK.EQ.3 .AND. SRC.EQ.5,ND6;    determine next node based
      ACT,,LINK.EQ.3 .AND. SRC.EQ.6,ND5;    on arriving link and last
      ACT,,LINK.EQ.4,ND6;                   transmitter
      ACT,,LINK.EQ.5 .AND. SRC.EQ.4,ND6;
      ACT,,LINK.EQ.5 .AND. SRC.EQ.6,ND4;
      ACT,,LINK.EQ.6 .AND. SRC.EQ.6,ND7;
      ACT,,LINK.EQ.6 .AND. SRC.EQ.7,ND6;
      ACT,,LINK.EQ.7 .AND. SRC.EQ.7,ND3;
      ACT,,LINK.EQ.7 .AND. SRC.EQ.3,ND7;
;
ND1   ASSIGN,SRC=1;                       message is at BEALE
      ACT,,,CHCK;
ND2   ASSIGN,SRC=2;                       message is at GOODFELLOW
      ACT,,,CHCK;
ND3   ASSIGN,SRC=3;                       message is at OTIS
      ACT,,,CHCK;
ND4   ASSIGN,SRC=4;                       message is at ROBINS
      ACT,,,CHCK;
ND5   ASSIGN,SRC=5;                       message is at CHEYENNE MOUNTAIN
      ACT,,,CHCK;
ND6   ASSIGN,SRC=6;                       message is at OMAHA
      ACT,,,CHCK;
ND7   ASSIGN,SRC=7;                       message is at RELAY
      ACT,,,CHCK;
CHCK  GOON,1;
      ACT,,SRC.EQ.DEST,DONE;              message is at destination
      ACT,,SRC.NE.DEST,XMIT;              message is at intermediate NODE
;
;
```

```
;--------------- Record Throughput and Delay Values ---------------
;
DONE  GOON,1;
      ACT,,DEST.EQ.5,WT5;     sort out msgs with CHEYENNE destination
      ACT,,DEST.EQ.6,WT6;     sort out msgs with OMAHA destination
      ACT,,DEST.NE.5 .OR. DEST.NE.6,EXIT;   terminate others
;
WT5   GOON,1;
        ACT,,ORIGIN.EQ.2,WT25;        calc waiting time from GOODFELLOW
        ACT,,ORIGIN.EQ.3,WT35;        calc waiting time from OTIS
        ACT,,ORIGIN.EQ.4,WT45;        calc waiting time from ROBINS
WT25  ASSIGN,WTSEC=TNOW-ATRIB(1);     calc message waiting time (sec)
      COLCT,WTSEC,GDFLW CHEY WT,15/0/10; GOODFELLOW WT histogram
      ASSIGN,NMSGS1=NMSGS1+1;         increment message counter
      ASSIGN,TPUT=MBITS*NMSGS1/TNOW;  all messages transmitted
      COLCT,TPUT,GDFLW CHEY TPUT;     record throughput
      ACT,,,EXIT;                     terminate message entity
WT35  ASSIGN,WTSEC=TNOW-ATRIB(1);     calc message waiting time (sec)
      COLCT,WTSEC,OTIS CHEY WT,15/0/10;  OTIS WT histogram
      ASSIGN,NMSGS2=NMSGS2+1;         increment message counter
      ASSIGN,TPUT=MBITS*NMSGS2/TNOW;  calculate throughput
      COLCT,TPUT,OTIS CHEY TPUT;      record throughput
      ACT,,,EXIT;                     terminate message entity
WT45  ASSIGN,WTSEC=TNOW-ATRIB(1);     calc message waiting time (sec)
      COLCT,WTSEC,ROBINS CHEY WT,15/0/10;  ROBINS WT histogram
      ASSIGN,NMSGS3=NMSGS3+1;         increment message counter
      ASSIGN,TPUT=MBITS*NMSGS3/TNOW;  calculate throughput
      COLCT,TPUT,ROBINS CHEY TPUT;    record throughput
      ACT,,,EXIT;                     terminate message entity
;
WT6   GOON,1;
        ACT,,ORIGIN.EQ.1,WT16;        calc waiting time from BEALE
        ACT,,ORIGIN.EQ.2,WT26;        calc waiting time from GOODFELLOW
WT16  ASSIGN,WTSEC=TNOW-ATRIB(1);     calc message waiting time (sec)
      COLCT,WTSEC,BEALE OMAHA WT,15/0/10;  BEALE WT histogram
      ASSIGN,NMSGS4=NMSGS4+1;         increment message counter
      ASSIGN,TPUT=MBITS*NMSGS4/TNOW;  calculate throughput
      COLCT,TPUT,BEALE OMAHA TPUT;    record throughput
      ACT,,,EXIT;                     terminate message entity
WT26  ASSIGN,WTSEC=TNOW-ATRIB(1);     calc message waiting time (sec)
      COLCT,WTSEC,GDFLW OMAHA WT,15/0/10;  GOODFELLOW WT histogram
      ASSIGN,NMSGS5=NMSGS5+1;         increment message counter
      ASSIGN,TPUT=MBITS*NMSGS5/TNOW;  calculate throughput
      COLCT,TPUT,GDFLW OMAHA TPUT;    record throughput
      ACT,,,EXIT;                     terminate message entity
;
;
EXIT  COLC,BET,TIME BET MSGS;
      TERM;                           terminate message
;
;
```

```
;--------------------- Message Overflows -----------------------
;
OVFL  COLCT,SRC,DISCARDED MSGS,6/1/1;  balk histogram for each node
      TERM;                             terminate balked messages
;
;
;--------------- Meteor Trail Arrival Process -----------------
;
;                        LINK 1 TRAILS
      CREATE,,.30,,1;                   wait for first trail preemption
TR1   PREEMPT(18),TRAIL1,,14;           end trail, discard remaining time
      ACT,EXPON(XX(51),1);              link 1 trail interarrival time
      FREE,TRAIL1/1;                    link 1 trail arrival
      ACT,EXPON(XX(52),1)-XX(53),,TR1;  link 1 trail duration - PDELAY
;

;                        LINK 2 TRAILS
      CREATE,,.30,,1;                   wait for first trail preemption
TR2   PREEMPT(19),TRAIL2,,14;           end trail, discard remaining time
      ACT,EXPON(XX(54),2);              link 2 trail interarrival time
      FREE,TRAIL2/1;                    link 2 trail arrival
      ACT,EXPON(XX(55),2)-XX(56),,TR2;  link 2 trail duration - PDELAY
;
;                        LINK 3 TRAILS
      CREATE,,.30,,1;                   wait for first trail preemption
TR3   PREEMPT(20),TRAIL3,,14;           end trail, discard remaining time
      ACT,EXPON(XX(57),3);              link 3 trail interarrival time
      FREE,TRAIL3/1;                    link 3 trail arrival
      ACT,EXPON(XX(58),3)-XX(59),,TR3;  link 3 trail duration - PDELAY
;
;                        LINK 4 TRAILS
      CREATE,,.30,,1;                   wait for first trail preemption
TR4   PREEMPT(21),TRAIL4,,14;           end trail, discard remaining time
      ACT,EXPON(XX(60),4);              link 4 trail interarrival time
      FREE,TRAIL4/1;                    link 4 trail arrival
      ACT,EXPON(XX(61),4)-XX(62),,TR4;  link 4 trail duration - PDELAY
;
;                        LINK 5 TRAILS
      CREATE,,.30,,1;                   wait for first trail preemption
TR5   PREEMPT(22),TRAIL5,,14;           end trail, discard remaining time
      ACT,EXPON(XX(63),5);              link 5 trail interarrival time
      FREE,TRAIL5/1;                    link 5 trail arrival
      ACT,EXPON(XX(64),5)-XX(65),,TR5;  link 5 trail duration - PDELAY
;
;                        LINK 6 TRAILS
      CREATE,,.30,,1;                   wait for first trail preemption
TR6   PREEMPT(23),TRAIL6,,14;           end trail, discard remaining time
      ACT,EXPON(XX(66),6);              link 6 trail interarrival time
      FREE,TRAIL6/1;                    link 6 trail arrival
      ACT,EXPON(XX(67),6)-XX(68),,TR6;  link 6 trail duration - PDELAY
;
```

```
;                         LINK 7 TRAILS
      CREATE,,.30,,1;                     wait for first trail preemption
TR7   PREEMPT(24),TRAIL7,,14;             end trail, discard remaining time
      ACT,EXPON(XX(69),7);                link 7 trail interarrival time
      FREE,TRAIL7/1;                      link 7 trail arrival
      ACT,EXPON(XX(70),8)-XX(71),,TR7;    link 7 trail duration - PDELAY
;
;                         LINK 8 TRAILS
      CREATE,,.30,,1;                     wait for first trail preemption
TR8   PREEMPT(25),TRAIL8,,14;             end trail, discard remaining time
      ACT,EXPON(XX(72),8);                link 8 trail interarrival time
      FREE,TRAIL8/1;                      link 8 trail arrival
      ACT,EXPON(XX(73),8)-XX(74),,TR8;    link 8 trail duration - PDELAY
;
      ENDNETWORK;
INIT,0,18000;                             Run sim for 5 hours (18000 sec)
MONTR,TRACE,0,100,SRC,DEST,LINK,MDUR,PDELAY,ORIGIN;
FIN;
```

Appendix G. *BLINK2 Run Time Results*

This appendix includes a sample of the BLINK2 run time results. The SPACECOM.DAT input data file was used to generate single-link results for the 7-node PAVEPAWS network.

NETWORK TOPOLOGY
****

SITE	NODE	LATITUDE	LONGITUDE
BEALE	1	39.20	121.50
GOODFELLOW	2	31.40	100.40
OTIS	3	41.70	70.50
ROBINS	4	32.60	83.60
CHEYENNE	5	38.80	104.80
OMAHA	6	41.20	96.00
RELAY1	7	41.00	87.00
RELAY2	8	48.00	108.00
RELAY3	9	32.00	111.00
RELAY4	10	36.00	93.00

MAXIMUM SINGLE HOP PATHS = 45

METEOR BURST INPUT SUMMARY
****

1	FREQUENCY =	30.0 MHz
2	MONTH =	JUL
3	HOUR =	11
4	TRANSMITTER POWER =	1000.0 Watts
5	TRANSMITTER GAIN =	10.0 dB
6	RECEIVER GAIN =	10.0 dB
7	BURST DATA RATE =	8000 bps
8	PROBE-RESPONSE DELAY =	0.030 sec
9	NUMBER BITS IN MSG BLOCK =	1024
10	WAITING TIME RELIABILITY =	99 %
11	RECEIVER/ANTENNA LINE LOSS =	1.0 dB
12	TOTAL SYSTEM LINE LOSSES =	1.0 dB
13	RECEIVER NOISE FACTOR =	4.0 dB
14	MAN-MADE NOISE FACTOR =	1.0

```
15   BIT ENERGY TO NOISE =                     9.0 dB
16   ELECTRON LINE DENSITY =               5.0E+13 el/m
     TERRAIN FACTOR =                            0
     NUMBER OF CASES =                           2
     PARAMETRIC VARIABLE =                   MONTH
     INCREMENTAL VALUE =                         7
     NUCLEAR ABSORPTION =                     0.00 dB
```

```
                    METEOR BURST LINK RESULTS
                    *************************


     ------ LINK BETWEEN BEALE AND CHEYENNE ---------
                         NODES 1 AND 5

                         CASE NUMBER  1
                         --------------
    MONTH                                 =     JUL
    RANGE                                 =  1440.9 km
    MESSAGE DURATION                      =   0.138 sec
    METEOR TRAIL DURATION                 =   0.450 sec
    METEOR TRAIL INTERARRIVAL TIME        =   8.723 sec
    DUTY CYCLE                            =    5.16 %
    BITS/BURST                            =    3284
    DIFFUSION COEFFICIENT                 =    10.6 m^2/sec
    AVERAGE METEOR TRAIL HEIGHT           =    98.9 meters
    METEOR TRAIL RADIUS                   =   1.026 meters
    ELECTRON LINE DENSITY                 = 5.0E+13 el/m
    UNADJUSTED METEOR BURSTS/MIN          =     6.9
    ADJUSTED METEOR BURSTS/MIN            =     4.6
    OPTIMUM BURST DATA RATE               =    5087 bps
    MAXIMUM BITS/BURST                    =    3990
    WAITING TIME RELIABILITY (WTREL)      =      99 %

1.  MESSAGE PIECING TRANSFER - PROTOCOL 1 RESULTS
         MAXIMUM THROUGHPUT = 307 bps
         MINIMUM TRANSMISSION TIME = 3.334 sec
         WAITING TIME AT WTREL = 43.401 sec

2.  SINGLE BURST TRANSFER - PROTOCOL 2 RESULTS
         APPROXIMATE THROUGHPUT = 75 bps
         APPROXIMATE TRANSMISSION TIME = 13.531 sec
         WAITING TIME AT WTREL = 60.634 sec


                         CASE NUMBER  2
                         --------------
    MONTH                                 =     FEB
    RANGE                                 =  1440.9 km
    MESSAGE DURATION                      =   0.138 sec
```

METEOR TRAIL DURATION	=	0.450 sec
METEOR TRAIL INTERARRIVAL TIME	=	51.214 sec
DUTY CYCLE	=	0.88 %
BITS/BURST	=	3284
DIFFUSION COEFFICIENT	=	10.6 m^2/sec
AVERAGE METEOR TRAIL HEIGHT	=	98.9 meters
METEOR TRAIL RADIUS	=	1.026 meters
ELECTRON LINE DENSITY	=	5.0E+13 el/m
UNADJUSTED METEOR BURSTS/MIN	=	1.2
ADJUSTED METEOR BURSTS/MIN	=	0.8
OPTIMUM BURST DATA RATE	=	5087 bps
MAXIMUM BITS/BURST	=	3990
WAITING TIME RELIABILITY (WTREL)	=	99 %

1. MESSAGE PIECING TRANSFER - PROTOCOL 1 RESULTS
   MAXIMUM THROUGHPUT = 52 bps
   MINIMUM TRANSMISSION TIME = 19.574 sec
   WAITING TIME AT WTREL = 254.807 sec

2. SINGLE BURST TRANSFER - PROTOCOL 2 RESULTS
   APPROXIMATE THROUGHPUT = 12 bps
   APPROXIMATE TRANSMISSION TIME = 79.438 sec
   WAITING TIME AT WTREL = 355.982 sec

------ LINK BETWEEN GOODFELLOW AND CHEYENNE --------
NODES 2 AND 5

CASE NUMBER 1

MONTH	=	JUL
RANGE	=	914.1 km
MESSAGE DURATION	=	0.134 sec
METEOR TRAIL DURATION	=	0.924 sec
METEOR TRAIL INTERARRIVAL TIME	=	6.049 sec
DUTY CYCLE	=	15.27 %
BITS/BURST	=	7099
DIFFUSION COEFFICIENT	=	10.6 m^2/sec
AVERAGE METEOR TRAIL HEIGHT	=	98.9 meters
METEOR TRAIL RADIUS	=	1.026 meters
ELECTRON LINE DENSITY	=	5.0E+13 el/m
UNADJUSTED METEOR BURSTS/MIN	=	9.9
ADJUSTED METEOR BURSTS/MIN	=	8.0
OPTIMUM BURST DATA RATE	=	18817 bps
MAXIMUM BITS/BURST	=	8703
WAITING TIME RELIABILITY (WTREL)	=	99 %

1. MESSAGE PIECING TRANSFER - PROTOCOL 1 RESULTS
   MAXIMUM THROUGHPUT = 696 bps
   MINIMUM TRANSMISSION TIME = 1.470 sec
   WAITING TIME AT WTREL = 28.872 sec

2. SINGLE BURST TRANSFER - PROTOCOL 2 RESULTS
   APPROXIMATE THROUGHPUT = 137 bps
   APPROXIMATE TRANSMISSION TIME = 7.464 sec
   WAITING TIME AT WTREL = 34.371 sec

CASE NUMBER 2

MONTH	=	FEB
RANGE	=	914.1 km
MESSAGE DURATION	=	0.134 sec
METEOR TRAIL DURATION	=	0.924 sec
METEOR TRAIL INTERARRIVAL TIME	=	35.515 sec
DUTY CYCLE	=	2.60 %
BITS/BURST	=	7099
DIFFUSION COEFFICIENT	=	10.6 m^2/sec
AVERAGE METEOR TRAIL HEIGHT	=	98.9 meters
METEOR TRAIL RADIUS	=	1.026 meters
ELECTRON LINE DENSITY	=	5.0E+13 el/m
UNADJUSTED METEOR BURSTS/MIN	=	1.7
ADJUSTED METEOR BURSTS/MIN	=	1.4
OPTIMUM BURST DATA RATE	=	18817 bps
MAXIMUM BITS/BURST	=	8703
WAITING TIME RELIABILITY (WTREL)	=	99 %

1. MESSAGE PIECING TRANSFER - PROTOCOL 1 RESULTS
   MAXIMUM THROUGHPUT = 118 bps
   MINIMUM TRANSMISSION TIME = 8.633 sec
   WAITING TIME AT WTREL = 169.509 sec

2. SINGLE BURST TRANSFER - PROTOCOL 2 RESULTS
   APPROXIMATE THROUGHPUT = 23 bps
   APPROXIMATE TRANSMISSION TIME = 43.821 sec
   WAITING TIME AT WTREL = 201.794 sec

----------- LINK BETWEEN GOODFELLOW AND OMAHA -------------
NODES 2 AND 6

CASE NUMBER 1

MONTH	=	JUL
RANGE	=	1157.7 km
MESSAGE DURATION	=	0.136 sec
METEOR TRAIL DURATION	=	0.789 sec
METEOR TRAIL INTERARRIVAL TIME	=	5.707 sec
DUTY CYCLE	=	13.82 %
BITS/BURST	=	6007
DIFFUSION COEFFICIENT	=	10.6 m^2/sec

AVERAGE METEOR TRAIL HEIGHT	=	98.9 meters
METEOR TRAIL RADIUS	=	1.026 meters
ELECTRON LINE DENSITY	=	5.0E+13 el/m
UNADJUSTED METEOR BURSTS/MIN	=	10.5
ADJUSTED METEOR BURSTS/MIN	=	8.2
OPTIMUM BURST DATA RATE	=	9609 bps
MAXIMUM BITS/BURST	=	6052
WAITING TIME RELIABILITY (WTREL)	=	99 %

1. MESSAGE PIECING TRANSFER - PROTOCOL 1 RESULTS
   MAXIMUM THROUGHPUT = 919 bps
   MINIMUM TRANSMISSION TIME = 1.113 sec
   WAITING TIME AT WTREL = 27.436 sec

2. SINGLE BURST TRANSFER - PROTOCOL 2 RESULTS
   APPROXIMATE THROUGHPUT = 139 bps
   APPROXIMATE TRANSMISSION TIME = 7.315 sec
   WAITING TIME AT WTREL = 33.569 sec

CASE NUMBER 2

MONTH	=	FEB
RANGE	=	1157.7 km
MESSAGE DURATION	=	0.136 sec
METEOR TRAIL DURATION	=	0.789 sec
METEOR TRAIL INTERARRIVAL TIME	=	33.507 sec
DUTY CYCLE	=	2.35 %
BITS/BURST	=	6007
DIFFUSION COEFFICIENT	=	10.6 m^2/sec
AVERAGE METEOR TRAIL HEIGHT	=	98.9 meters
METEOR TRAIL RADIUS	=	1.026 meters
ELECTRON LINE DENSITY	=	5.0E+13 el/m
UNADJUSTED METEOR BURSTS/MIN	=	1.8
ADJUSTED METEOR BURSTS/MIN	=	1.4
OPTIMUM BURST DATA RATE	=	9609 bps
MAXIMUM BITS/BURST	=	6052
WAITING TIME RELIABILITY (WTREL)	=	99 %

1. MESSAGE PIECING TRANSFER - PROTOCOL 1 RESULTS
   MAXIMUM THROUGHPUT = 156 bps
   MINIMUM TRANSMISSION TIME = 6.537 sec
   WAITING TIME AT WTREL = 161.073 sec

2. SINGLE BURST TRANSFER - PROTOCOL 2 RESULTS
   APPROXIMATE THROUGHPUT = 23 bps
   APPROXIMATE TRANSMISSION TIME = 42.946 sec
   WAITING TIME AT WTREL = 197.083 sec

----------- LINK BETWEEN CHEYENNE AND OMAHA -------------
NODES 5 AND 6

CASE NUMBER 1

MONTH	=	JUL
RANGE	=	794.7 km
MESSAGE DURATION	=	0.133 sec
METEOR TRAIL DURATION	=	0.919 sec
METEOR TRAIL INTERARRIVAL TIME	=	6.579 sec
DUTY CYCLE	=	13.96 %
BITS/BURST	=	7066
DIFFUSION COEFFICIENT	=	10.6 m^2/sec
AVERAGE METEOR TRAIL HEIGHT	=	98.9 meters
METEOR TRAIL RADIUS	=	1.026 meters
ELECTRON LINE DENSITY	=	5.0E+13 el/m
UNADJUSTED METEOR BURSTS/MIN	=	9.1
ADJUSTED METEOR BURSTS/MIN	=	7.4
OPTIMUM BURST DATA RATE	=	27750 bps
MAXIMUM BITS/BURST	=	10399
WAITING TIME RELIABILITY (WTREL)	=	99 %

1. MESSAGE PIECING TRANSFER - PROTOCOL 1 RESULTS
   MAXIMUM THROUGHPUT = 637 bps
   MINIMUM TRANSMISSION TIME = 1.607 sec
   WAITING TIME AT WTREL = 31.394 sec

2. SINGLE BURST TRANSFER - PROTOCOL 2 RESULTS
   APPROXIMATE THROUGHPUT = 126 bps
   APPROXIMATE TRANSMISSION TIME = 8.120 sec
   WAITING TIME AT WTREL = 37.386 sec

CASE NUMBER 2

MONTH	=	FEB
RANGE	=	794.7 km
MESSAGE DURATION	=	0.133 sec
METEOR TRAIL DURATION	=	0.919 sec
METEOR TRAIL INTERARRIVAL TIME	=	38.626 sec
DUTY CYCLE	=	2.38 %
BITS/BURST	=	7066
DIFFUSION COEFFICIENT	=	10.6 m^2/sec
AVERAGE METEOR TRAIL HEIGHT	=	98.9 meters
METEOR TRAIL RADIUS	=	1.026 meters
ELECTRON LINE DENSITY	=	5.0E+13 el/m
UNADJUSTED METEOR BURSTS/MIN	=	1.6
ADJUSTED METEOR BURSTS/MIN	=	1.3
OPTIMUM BURST DATA RATE	=	27750 bps
MAXIMUM BITS/BURST	=	10399
WAITING TIME RELIABILITY (WTREL)	=	99 %

1. MESSAGE PIECING TRANSFER - PROTOCOL 1 RESULTS
   MAXIMUM THROUGHPUT = 108 bps
   MINIMUM TRANSMISSION TIME = 9.432 sec
   WAITING TIME AT WTREL = 184.314 sec

2. SINGLE BURST TRANSFER - PROTOCOL 2 RESULTS
   APPROXIMATE THROUGHPUT = 21 bps
   APPROXIMATE TRANSMISSION TIME = 47.673 sec
   WAITING TIME AT WTREL = 219.494 sec

----------- LINK BETWEEN ROBINS AND OMAHA ------------

NODES 4 AND 6

CASE NUMBER 1

MONTH	=	JUL
RANGE	=	1455.9 km
MESSAGE DURATION	=	0.138 sec
METEOR TRAIL DURATION	=	0.429 sec
METEOR TRAIL INTERARRIVAL TIME	=	8.946 sec
DUTY CYCLE	=	4.79 %
BITS/BURST	=	3111
DIFFUSION COEFFICIENT	=	10.6 m^2/sec
AVERAGE METEOR TRAIL HEIGHT	=	98.9 meters
METEOR TRAIL RADIUS	=	1.026 meters
ELECTRON LINE DENSITY	=	5.0E+13 el/m
UNADJUSTED METEOR BURSTS/MIN	=	6.7
ADJUSTED METEOR BURSTS/MIN	=	4.4
OPTIMUM BURST DATA RATE	=	4934 bps
MAXIMUM BITS/BURST	=	3904
WAITING TIME RELIABILITY (WTREL)	=	99 %

1. MESSAGE PIECING TRANSFER - PROTOCOL 1 RESULTS
   MAXIMUM THROUGHPUT = 281 bps
   MINIMUM TRANSMISSION TIME = 3.635 sec
   WAITING TIME AT WTREL = 44.690 sec

2. SINGLE BURST TRANSFER - PROTOCOL 2 RESULTS
   APPROXIMATE THROUGHPUT = 72 bps
   APPROXIMATE TRANSMISSION TIME = 14.190 sec
   WAITING TIME AT WTREL = 63.389 sec

CASE NUMBER 2

MONTH	=	FEB
RANGE	=	1455.9 km
MESSAGE DURATION	=	0.138 sec
METEOR TRAIL DURATION	=	0.429 sec

```
     METEOR TRAIL INTERARRIVAL TIME    =  52.524 sec
     DUTY CYCLE                        =    0.82 %
     BITS/BURST                        =    3111
     DIFFUSION COEFFICIENT             =    10.6 m^2/sec
     AVERAGE METEOR TRAIL HEIGHT       =    98.9 meters
     METEOR TRAIL RADIUS               =   1.026 meters
     ELECTRON LINE DENSITY             = 5.0E+13 el/m
     UNADJUSTED METEOR BURSTS/MIN      =     1.1
     ADJUSTED METEOR BURSTS/MIN        =     0.7
     OPTIMUM BURST DATA RATE           =    4934 bps
     MAXIMUM BITS/BURST                =    3904
     WAITING TIME RELIABILITY (WTREL) =       99 %

1.   MESSAGE PIECING TRANSFER - PROTOCOL 1 RESULTS
          MAXIMUM THROUGHPUT = 47 bps
          MINIMUM TRANSMISSION TIME = 21.344 sec
          WAITING TIME AT WTREL = 262.372 sec

2.   SINGLE BURST TRANSFER - PROTOCOL 2 RESULTS
          APPROXIMATE THROUGHPUT = 12 bps
          APPROXIMATE TRANSMISSION TIME = 83.306 sec
          WAITING TIME AT WTREL = 372.153 sec


----------- LINK BETWEEN OTIS AND RELAY1 -------------
                     NODES 3 AND 7

                     CASE NUMBER  1
                     --------------
     MONTH                             =     JUL
     RANGE                             =  1376.5 km
     MESSAGE DURATION                  =   0.137 sec
     METEOR TRAIL DURATION             =   0.539 sec
     METEOR TRAIL INTERARRIVAL TIME    =   7.860 sec
     DUTY CYCLE                        =    6.86 %
     BITS/BURST                        =    3999
     DIFFUSION COEFFICIENT             =    10.6 m^2/sec
     AVERAGE METEOR TRAIL HEIGHT       =    98.9 meters
     METEOR TRAIL RADIUS               =   1.026 meters
     ELECTRON LINE DENSITY             = 5.0E+13 el/m
     UNADJUSTED METEOR BURSTS/MIN      =     7.6
     ADJUSTED METEOR BURSTS/MIN        =     5.4
     OPTIMUM BURST DATA RATE           =    5814 bps
     MAXIMUM BITS/BURST                =    4383
     WAITING TIME RELIABILITY (WTREL) =       99 %

1.   MESSAGE PIECING TRANSFER - PROTOCOL 1 RESULTS
          MAXIMUM THROUGHPUT = 425 bps
          MINIMUM TRANSMISSION TIME = 2.408 sec
          WAITING TIME AT WTREL = 38.597 sec
```

2. SINGLE BURST TRANSFER - PROTOCOL 2 RESULTS
APPROXIMATE THROUGHPUT = 90 bps
APPROXIMATE TRANSMISSION TIME = 11.332 sec
WAITING TIME AT WTREL = 51.285 sec

CASE NUMBER 2

MONTH	=	FEB
RANGE	=	1376.5 km
MESSAGE DURATION	=	0.137 sec
METEOR TRAIL DURATION	=	0.539 sec
METEOR TRAIL INTERARRIVAL TIME	=	46.148 sec
DUTY CYCLE	=	1.17 %
BITS/BURST	=	3999
DIFFUSION COEFFICIENT	=	10.6 m^2/sec
AVERAGE METEOR TRAIL HEIGHT	=	98.9 meters
METEOR TRAIL RADIUS	=	1.026 meters
ELECTRON LINE DENSITY	=	5.0E+13 el/m
UNADJUSTED METEOR BURSTS/MIN	=	1.3
ADJUSTED METEOR BURSTS/MIN	=	0.9
OPTIMUM BURST DATA RATE	=	5814 bps
MAXIMUM BITS/BURST	=	4383
WAITING TIME RELIABILITY (WTREL)	=	99 %

1. MESSAGE PIECING TRANSFER - PROTOCOL 1 RESULTS
MAXIMUM THROUGHPUT = 72 bps
MINIMUM TRANSMISSION TIME = 14.138 sec
WAITING TIME AT WTREL = 226.603 sec

2. SINGLE BURST TRANSFER - PROTOCOL 2 RESULTS
APPROXIMATE THROUGHPUT = 15 bps
APPROXIMATE TRANSMISSION TIME = 66.528 sec
WAITING TIME AT WTREL = 301.095 sec

----------- LINK BETWEEN RELAY1 AND OMAHA ------------
NODES 7 AND 6

CASE NUMBER 1

MONTH	=	JUL
RANGE	=	753.6 km
MESSAGE DURATION	=	0.133 sec
METEOR TRAIL DURATION	=	0.905 sec
METEOR TRAIL INTERARRIVAL TIME	=	6.798 sec
DUTY CYCLE	=	13.32 %
BITS/BURST	=	6961
DIFFUSION COEFFICIENT	=	10.6 m^2/sec
AVERAGE METEOR TRAIL HEIGHT	=	98.9 meters
METEOR TRAIL RADIUS	=	1.026 meters
ELECTRON LINE DENSITY	=	5.0E+13 el/m

UNADJUSTED METEOR BURSTS/MIN	=	8.8
ADJUSTED METEOR BURSTS/MIN	=	7.1
OPTIMUM BURST DATA RATE	=	32077 bps
MAXIMUM BITS/BURST	=	11051
WAITING TIME RELIABILITY (WTREL)	=	99 %

1. MESSAGE PIECING TRANSFER - PROTOCOL 1 RESULTS
   MAXIMUM THROUGHPUT = 607 bps
   MINIMUM TRANSMISSION TIME = 1.685 sec
   WAITING TIME AT WTREL = 32.449 sec

2. SINGLE BURST TRANSFER - PROTOCOL 2 RESULTS
   APPROXIMATE THROUGHPUT = 121 bps
   APPROXIMATE TRANSMISSION TIME = 8.413 sec
   WAITING TIME AT WTREL = 38.725 sec

CASE NUMBER 2

MONTH	=	FEB
RANGE	=	753.6 km
MESSAGE DURATION	=	0.133 sec
METEOR TRAIL DURATION	=	0.905 sec
METEOR TRAIL INTERARRIVAL TIME	=	39.909 sec
DUTY CYCLE	=	2.27 %
BITS/BURST	=	6961
DIFFUSION COEFFICIENT	=	10.6 m^2/sec
AVERAGE METEOR TRAIL HEIGHT	=	98.9 meters
METEOR TRAIL RADIUS	=	1.026 meters
ELECTRON LINE DENSITY	=	5.0E+13 el/m
UNADJUSTED METEOR BURSTS/MIN	=	1.5
ADJUSTED METEOR BURSTS/MIN	=	1.2
OPTIMUM BURST DATA RATE	=	32077 bps
MAXIMUM BITS/BURST	=	11051
WAITING TIME RELIABILITY (WTREL)	=	99 %

1. MESSAGE PIECING TRANSFER - PROTOCOL 1 RESULTS
   MAXIMUM THROUGHPUT = 103 bps
   MINIMUM TRANSMISSION TIME = 9.890 sec
   WAITING TIME AT WTREL = 190.508 sec

2. SINGLE BURST TRANSFER - PROTOCOL 2 RESULTS
   APPROXIMATE THROUGHPUT = 20 bps
   APPROXIMATE TRANSMISSION TIME = 49.395 sec
   WAITING TIME AT WTREL = 227.353 sec

Appendix H. *PAVE PAWS Network Run Time Results*

This appendix includes selected SLAM II run time results. These results were selected from the 7-node PAVEPAWS network.

S L A M   I I   S U M M A R Y   R E P O R T

SIMULATION PROJECT PAVEPAWS MBC NETWORK   BY HEALY

DATE 9/14/1988   RUN NUMBER 1 OF 1

CURRENT TIME .1800E+05
STATISTICAL ARRAYS CLEARED AT TIME .0000E+00

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
BEALE mps	.300E+01	.000E+00	.000E+00	.300E+01	.300E+01	855
GOODFELLOW mps	.300E+01	.000E+00	.000E+00	.300E+01	.300E+01	871
OTIS mps	.300E+01	.000E+00	.000E+00	.300E+01	.300E+01	877
ROBINS mps	.300E+01	.000E+00	.000E+00	.300E+01	.300E+01	867
CHEYENNE mps	.100E+00	.000E+00	.000E+00	.100E+00	.100E+00	31
LINK 1 XBAR	.107E+02	.161E+02	.151E+01	.104E+00	.108E+03	853
LINK 2 XBAR	.841E+01	.129E+02	.153E+01	.101E+00	.812E+02	871
LINK 4 XBAR	.574E+01	.945E+01	.164E+01	.103E+00	.791E+02	871
LINK 7 XBAR	.963E+01	.146E+02	.152E+01	.104E+00	.129E+03	877
LINK 5 XBAR	.164E+02	.238E+02	.145E+01	.104E+00	.165E+03	862
LINK 3 XBAR	.910E+01	.150E+02	.165E+01	.996E-01	.110E+03	853
LINK 6 XBAR	.924E+01	.160E+02	.174E+01	.996E-01	.118E+03	873
GDFLW CHEY WT	.189E+02	.163E+02	.863E+00	.101E+00	.887E+02	871
GDFLW CHEY TPUT	.320E+02	.173E+03	.542E+01	.240E+02	.514E+04	871
OTIS CHEY WT	.807E+02	.494E+02	.612E+00	.176E+01	.267E+03	872
OTIS CHEY TPUT	.248E+02	.928E+01	.374E+00	.103E+02	.296E+03	872
ROBINS CHEY WT	.108E+03	.788E+02	.730E+00	.205E+00	.427E+03	862
ROBINS CHEY TPUT	.280E+02	.856E+02	.305E+01	.794E+01	.254E+04	862
BEALE OMAHA WT	.481E+02	.307E+02	.637E+00	.205E+00	.182E+03	853
BEALE OMAHA TPUT	.241E+02	.153E+01	.633E-01	.148E+02	.454E+02	853

GDFLW OMAHA WT	.444E+02	.382E+02	.859E+00	.204E+00	.269E+03	871
GDFLW OMAHA TPUT	.287E+02	.856E+02	.299E+01	.239E+02	.255E+04	871
TIME BET MSGS	.405E+01	.768E+01	.190E+01	.488E-03	.677E+02	4448
DISCARDED MSGS			NO VALUES RECORDED			

FILE STATISTICS

FILE NUMBER	ASSOC NODE LABEL/TYPE	AVERAGE LENGTH	STANDARD DEVIATION	MAXIMUM LENGTH	CURRENT LENGTH	AVERAGE WAIT TIME
1	XMB1 AWAIT	.532	.549	2	2	10.825
2	XMG2 AWAIT	.421	.524	2	0	8.418
3	XMC3 AWAIT	1.064	.799	2	1	7.232
4	XMG4 AWAIT	.273	.445	1	0	5.641
5	XMR5 AWAIT	.833	.470	2	1	16.787
6	XOM6 AWAIT	.472	.537	2	1	9.389
7	XMO7 AWAIT	.492	.537	2	0	9.758
8		.000	.000	0	0	.000
9		.000	.000	0	0	.000
10	BFF1 AWAIT	.490	1.091	9	1	10.314
11	BF2A AWAIT	.509	.969	7	0	10.513
12	BF2B AWAIT	1.871	2.424	14	0	38.675
13	BFF3 AWAIT	.404	.912	7	0	8.287
14	BFF4 AWAIT	2.708	3.453	20	4	56.214
15	BFF5 AWAIT	1.103	1.990	15	3	20.326
16	BFF6 AWAIT	2.978	4.176	25	0	29.862
17	BFF7 AWAIT	.754	1.498	9	3	14.967
18	TR1 PREEMPT	.000	.000	1	0	.000
19	TR2 PREEMPT	.000	.000	1	0	.000
20	TR3 PREEMPT	.000	.000	1	0	.000
21	TR4 PREEMPT	.000	.000	1	0	.000
22	TR5 PREEMPT	.000	.000	1	0	.000
23	TR6 PREEMPT	.000	.000	1	0	.000
24	TR7 PREEMPT	.000	.000	1	0	.000
25	TR8 PREEMPT	.000	.000	1	0	.000
26	CALENDAR	13.051	.225	22	13	1.528

REGULAR ACTIVITY STATISTICS

ACTIVITY INDEX/LABEL	AVERAGE UTILIZATION	STANDARD DEVIATION	MAXIMUM UTIL	CURRENT UTIL	ENTITY COUNT
1 LINK 1 XMIT	.0050	.0709	1	0	883
2 LINK 2 XMIT	.0050	.0705	1	0	901
3 LINK 3 XMIT	.0146	.1199	1	0	2647
4 LINK 4 XMIT	.0050	.0703	1	0	871
5 LINK 5 XMIT	.0051	.0713	1	0	892
6 LINK 6 XMIT	.0049	.0700	1	0	903
7 LINK 7 XMIT	.0052	.0717	1	0	907

RESOURCE STATISTICS

RESOURCE NUMBER	RESOURCE LABEL	CURRENT CAPACITY	AVERAGE UTIL	STANDARD DEVIATION	MAXIMUM UTIL	CURRENT UTIL
1	XMITTER1	1	.51	.500	1	1
2	XMITTER2	1	.68	.465	1	0
3	XMITTER3	1	.47	.499	1	0
4	XMITTER4	1	.79	.409	1	1
5	XMITTER5	1	.51	.500	1	1
6	XMITTER6	1	.69	.461	1	1
7	XMITTER7	1	.48	.499	1	1
8	TRAIL1	1	.97	.158	1	1
9	TRAIL2	1	.95	.209	1	1
10	TRAIL3	1	.98	.132	1	1
11	TRAIL4	1	.93	.254	1	1
12	TRAIL5	1	1.00	.059	1	1
13	TRAIL6	1	.97	.158	1	1
14	TRAIL7	1	.97	.176	1	1
15	TRAIL8	1	.95	.220	1	1

RESOURCE NUMBER	RESOURCE LABEL	CURRENT AVAILABLE	AVERAGE AVAILABLE	MINIMUM AVAILABLE	MAXIMUM AVAILABLE
1	XMITTER1	0	.4938	0	1
2	XMITTER2	1	.3154	0	1
3	XMITTER3	1	.5307	0	1
4	XMITTER4	0	.2120	0	1
5	XMITTER5	0	.4885	0	1
6	XMITTER6	0	.3053	0	1
7	XMITTER7	0	.5233	0	1
8	TRAIL1	0	.0257	0	1
9	TRAIL2	0	.0457	0	1
10	TRAIL3	0	.0179	0	1
11	TRAIL4	0	.0695	0	1
12	TRAIL5	0	.0035	0	1
13	TRAIL6	0	.0256	0	1
14	TRAIL7	0	.0320	0	1
15	TRAIL8	0	.0511	0	1

HISTOGRAM NUMBER 6
LINK 1 XBAR

```
OBS  RELA   UPPER
FREQ FREQ  CELL LIM 0         20        40        60        80       100
                    +    +    +    +    +    +    +    +    +    +    +
  0  .000  .000E+00 +                                                 +
416  .488  .300E+01 +************************                         +
 74  .087  .600E+01 +****                        C                    +
 65  .076  .900E+01 +****                            C                +
 44  .052  .120E+02 +***                               C              +
 36  .042  .150E+02 +**                                  C            +
 28  .033  .180E+02 +**                                    C          +
 29  .034  .210E+02 +**                                      C        +
 31  .036  .240E+02 +**                                       C       +
 20  .023  .270E+02 +*                                          C     +
 15  .018  .300E+02 +*                                          C     +
 12  .014  .330E+02 +*                                           C    +
  8  .009  .360E+02 +                                             C   +
 16  .019  .390E+02 +*                                             C  +
 10  .012  .420E+02 +*                                             C  +
 10  .012  .450E+02 +*                                              C +
 39  .046    INF    +**                                               C
---                 +    +    +    +    +    +    +    +    +    +    +
853                 0         20        40        60        80       100
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
LINK 1 XBAR	.107E+02	.161E+02	.151E+01	.104E+00	.108E+03	853

HISTOGRAM NUMBER 7
LINK 2 XBAR

```
OBS  RELA   UPPER
FREQ FREQ  CELL LIM 0         20        40        60        80      100
                    +    +    +    +    +    +    +    +    +    +    +
   0 .000  .000E+00 +                                                 +
 471 .541  .300E+01 +***************************                      +
  62 .071  .600E+01 +****                          C                  +
  60 .069  .900E+01 +***                              C               +
  52 .060  .120E+02 +***                                 C            +
  37 .042  .150E+02 +**                                    C          +
  40 .046  .180E+02 +**                                      C        +
  29 .033  .210E+02 +**                                        C      +
  24 .028  .240E+02 +*                                          C     +
  17 .020  .270E+02 +*                                           C    +
  20 .023  .300E+02 +*                                             C  +
   9 .010  .330E+02 +*                                             C  +
   7 .008  .360E+02 +                                               C +
  12 .014  .390E+02 +*                                              C +
   6 .007  .420E+02 +                                                C+
   5 .006  .450E+02 +                                                C+
  20 .023    INF    +*                                                C
 ---                +    +    +    +    +    +    +    +    +    +    +
 871                0         20        40        60        80      100
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
LINK 2 XBAR	.841E+01	.129E+02	.153E+01	.101E+00	.812E+02	871

HISTOGRAM NUMBER 8
LINK 4 XBAR

```
OBS   RELA   UPPER
FREQ  FREQ  CELL LIM 0        20        40        60        80       100
                     +    +    +    +    +    +    +    +    +    +    +
   0  .000  .000E+00 +                                                 +
 524  .602  .300E+01 +******************************                   +
  71  .082  .600E+01 +****                             C               +
  72  .083  .900E+01 +****                                 C           +
  53  .061  .120E+02 +***                                     C        +
  38  .044  .150E+02 +**                                         C    +
  26  .030  .180E+02 +*                                           C   +
  31  .036  .210E+02 +**                                            C  +
  11  .013  .240E+02 +*                                             C  +
  10  .011  .270E+02 +*                                              C +
   6  .007  .300E+02 +                                               C +
   8  .009  .330E+02 +                                                C+
   6  .007  .360E+02 +                                                C+
   2  .002  .390E+02 +                                                C+
   5  .006  .420E+02 +                                                 C
   1  .001  .450E+02 +                                                 C
   7  .008    INF    +                                                 C
 ---                 +    +    +    +    +    +    +    +    +    +    +
 871                 0        20        40        60        80       100
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
LINK 4 XBAR	.574E+01	.945E+01	.164E+01	.103E+00	.791E+02	871

HISTOGRAM NUMBER 9

LINK 7 XBAR

```
OBS   RELA  UPPER
FREQ  FREQ  CELL LIM  0         20        40        60        80        100
                      +    +    +    +    +    +    +    +    +    +    +
   0  .000  .000E+00  +                                                 +
 460  .525  .300E+01  +*************************                        +
  61  .070  .600E+01  +***                          C                   +
  49  .056  .900E+01  +***                            C                 +
  54  .062  .120E+02  +***                                C             +
  34  .039  .150E+02  +**                                   C           +
  42  .048  .180E+02  +**                                     C         +
  31  .035  .210E+02  +**                                       C       +
  26  .030  .240E+02  +*                                         C      +
  19  .022  .270E+02  +*                                          C     +
  18  .021  .300E+02  +*                                           C    +
  16  .018  .330E+02  +*                                            C   +
  14  .016  .360E+02  +*                                             C  +
   9  .010  .390E+02  +*                                             C  +
   8  .009  .420E+02  +                                               C +
   6  .007  .450E+02  +                                               C +
  30  .034    INF     +**                                               C
 ---                  +    +    +    +    +    +    +    +    +    +    +
 877                  0         20        40        60        80        100
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
LINK 7 XBAR	.963E+01	.146E+02	.152E+01	.104E+00	.129E+03	877

HISTOGRAM NUMBER10
LINK 5 XBAR

```
OBS  RELA   UPPER
FREQ FREQ  CELL LIM 0        20        40        60        80       100
                    +    +    +    +    +    +    +    +    +    +    +
  0  .000  .000E+00 +                                                 +
391  .454  .300E+01 +***********************                          +
 52  .060  .600E+01 +***                      C                       +
 48  .056  .900E+01 +***                        C                     +
 29  .034  .120E+02 +**                           C                   +
 36  .042  .150E+02 +**                             C                 +
 25  .029  .180E+02 +*                                C               +
 26  .030  .210E+02 +**                                C              +
 29  .034  .240E+02 +**                                  C            +
 18  .021  .270E+02 +*                                    C           +
 24  .028  .300E+02 +*                                     C          +
 15  .017  .330E+02 +*                                      C         +
 30  .035  .360E+02 +**                                       C       +
 14  .016  .390E+02 +*                                         C      +
 16  .019  .420E+02 +*                                          C     +
 16  .019  .450E+02 +*                                           C    +
 93  .108    INF     +*****                                            C
---                 +    +    +    +    +    +    +    +    +    +    +
862                 0        20        40        60        80       100
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
LINK 5 XBAR	.164E+02	.238E+02	.145E+01	.104E+00	.165E+03	862

HISTOGRAM NUMBER11

LINK 3 XBAR

```
OBS  RELA   UPPER
FREQ FREQ  CELL LIM 0        20        40        60        80       100
                    +    +    +    +    +    +    +    +    +    +    +
  0  .000  .000E+00 +                                                 +
491  .576  .300E+01 +*****************************                    +
 60  .070  .600E+01 +****                           C                 +
 46  .054  .900E+01 +***                               C              +
 45  .053  .120E+02 +***                                  C           +
 27  .032  .150E+02 +**                                    C          +
 13  .015  .180E+02 +*                                      C         +
 30  .035  .210E+02 +**                                       C       +
 20  .023  .240E+02 +*                                         C      +
 17  .020  .270E+02 +*                                          C     +
 17  .020  .300E+02 +*                                           C    +
 12  .014  .330E+02 +*                                            C   +
 16  .019  .360E+02 +*                                             C  +
  8  .009  .390E+02 +                                              C  +
 12  .014  .420E+02 +*                                              C +
  5  .006  .450E+02 +                                               C +
 34  .040    INF    +**                                               C
---                 +    +    +    +    +    +    +    +    +    +    +
853                 0        20        40        60        80       100
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
LINK 3 XBAR	.910E+01	.150E+02	.165E+01	.996E-01	.110E+03	853

HISTOGRAM NUMBER12
LINK 6 XBAR

```
OBS  RELA     UPPER
FREQ FREQ   CELL LIM 0        20        40        60        80       100
                     +    +    +    +    +    +    +    +    +    +    +
  0  .000   .000E+00 +                                                 +
514  .589   .300E+01 +*****************************                    +
 52  .060   .600E+01 +***                            C                 +
 40  .046   .900E+01 +**                                C              +
 40  .046   .120E+02 +**                                  C            +
 29  .033   .150E+02 +**                                    C          +
 33  .038   .180E+02 +**                                      C        +
 20  .023   .210E+02 +*                                        C       +
 19  .022   .240E+02 +*                                         C      +
 21  .024   .270E+02 +*                                          C     +
 14  .016   .300E+02 +*                                           C    +
 16  .018   .330E+02 +*                                            C   +
 12  .014   .360E+02 +*                                            C   +
 11  .013   .390E+02 +*                                             C  +
 11  .013   .420E+02 +*                                              C +
 10  .011   .450E+02 +*                                              C +
 31  .036      INF   +**                                               C
---                  +    +    +    +    +    +    +    +    +    +    +
873                  0        20        40        60        80       100
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
LINK 6 XBAR	.924E+01	.160E+02	.174E+01	.996E-01	.118E+03	873

HISTOGRAM NUMBER13

GDFLW CHEY WT

```
OBS  RELA   UPPER
FREQ FREQ  CELL LIM 0        20        40        60        80       100
                    +    +    +    +    +    +    +    +    +    +    +
  0  .000  .000E+00 +                                                 +
296  .340  .100E+02 +*****************                                +
255  .293  .200E+02 +***************                C                 +
148  .170  .300E+02 +********                               C         +
 69  .079  .400E+02 +****                                       C     +
 51  .059  .500E+02 +***                                           C  +
 26  .030  .600E+02 +*                                               C+
 16  .018  .700E+02 +*                                               C+
  6  .007  .800E+02 +                                                 C
  4  .005  .900E+02 +                                                 C
  0  .000  .100E+03 +                                                 C
  0  .000  .110E+03 +                                                 C
  0  .000  .120E+03 +                                                 C
  0  .000  .130E+03 +                                                 C
  0  .000  .140E+03 +                                                 C
  0  .000  .150E+03 +                                                 C
  0  .000    INF    +                                                 C
---                 +    +    +    +    +    +    +    +    +    +    +
871                 0        20        40        60        80       100
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
GDFLW CHEY WT	.189E+02	.163E+02	.863E+00	.101E+00	.887E+02	871

HISTOGRAM NUMBER15
OTIS CHEY WT

```
 OBS  RELA   UPPER
FREQ  FREQ  CELL LIM 0         20        40        60        80        100
                     +    +    +    +    +    +    +    +    +    +    +
   0  .000  .000E+00 +                                                 +
   6  .007  .100E+02 +                                                 +
  37  .042  .200E+02 +**                                               +
  75  .086  .300E+02 +****  C                                          +
  77  .088  .400E+02 +****      C                                      +
  78  .089  .500E+02 +****           C                                 +
  65  .075  .600E+02 +****              C                              +
  77  .088  .700E+02 +****                   C                         +
  75  .086  .800E+02 +****                       C                     +
  72  .083  .900E+02 +****                           C                 +
  60  .069  .100E+03 +***                                C             +
  50  .057  .110E+03 +***                                   C          +
  41  .047  .120E+03 +**                                      C        +
  37  .042  .130E+03 +**                                        C      +
  24  .028  .140E+03 +*                                          C     +
  19  .022  .150E+03 +*                                           C    +
  79  .091    INF    +*****                                            C
 ---                 +    +    +    +    +    +    +    +    +    +    +
 872                 0         20        40        60        80        100
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
OTIS CHEY WT	.807E+02	.494E+02	.612E+00	.176E+01	.267E+03	872

HISTOGRAM NUMBER17
ROBINS CHEY WT

```
OBS  RELA   UPPER
FREQ FREQ  CELL LIM 0         20        40        60        80      100
                    +    +    +    +    +    +    +    +    +    +    +
  0  .000  .000E+00 +                                                 +
 14  .016  .100E+02 +*                                                +
 43  .050  .200E+02 +**C                                              +
 39  .045  .300E+02 +**   C                                           +
 50  .058  .400E+02 +***    C                                         +
 73  .085  .500E+02 +****        C                                    +
 70  .081  .600E+02 +****            C                                +
 68  .079  .700E+02 +****                C                            +
 50  .058  .800E+02 +***                    C                         +
 42  .049  .900E+02 +**                       C                       +
 45  .052  .100E+03 +***                         C                    +
 38  .044  .110E+03 +**                            C                  +
 34  .039  .120E+03 +**                              C                +
 35  .041  .130E+03 +**                                C              +
 23  .027  .140E+03 +*                                  C             +
 23  .027  .150E+03 +*                                    C           +
215  .249    INF    +************                                     C
---                 +    +    +    +    +    +    +    +    +    +    +
862                 0         20        40        60        80      100
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
ROBINS CHEY WT	.108E+03	.788E+02	.730E+00	.205E+00	.427E+03	862

HISTOGRAM NUMBER19
BEALE OMAHA WT

```
OBS  RELA   UPPER
FREQ FREQ  CELL LIM 0        20        40        60        80       100
                    +    +    +    +    +    +    +    +    +    +    +
  0  .000  .000E+00 +                                                 +
 47  .055  .100E+02 +***                                              +
 94  .110  .200E+02 +****** C                                         +
129  .151  .300E+02 +********       C                                 +
120  .141  .400E+02 +*******               C                          +
121  .142  .500E+02 +*******                      C                   +
 94  .110  .600E+02 +******                            C              +
 69  .081  .700E+02 +****                                   C         +
 55  .064  .800E+02 +***                                       C      +
 45  .053  .900E+02 +***                                         C    +
 22  .026  .100E+03 +*                                             C  +
 19  .022  .110E+03 +*                                              C +
 12  .014  .120E+03 +*                                              C +
 10  .012  .130E+03 +*                                               C+
  6  .007  .140E+03 +                                                C+
  3  .004  .150E+03 +                                                 C
  7  .008    INF    +                                                 C
---                 +    +    +    +    +    +    +    +    +    +    +
853                 0        20        40        60        80       100
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
BEALE OMAHA WT	.481E+02	.307E+02	.637E+00	.205E+00	.182E+03	853

HISTOGRAM NUMBER21
GDFLW OMAHA WT

```
OBS  RELA   UPPER
FREQ FREQ  CELL LIM 0        20        40        60        80       100
                    +    +    +    +    +    +    +    +    +    +    +
  0  .000  .000E+00 +                                                 +
 88  .101  .100E+02 +*****                                            +
160  .184  .200E+02 +**********   C                                   +
136  .156  .300E+02 +*********            C                           +
121  .139  .400E+02 +********                    C                    +
 98  .113  .500E+02 +*******                           C              +
 59  .068  .600E+02 +***                                  C           +
 38  .044  .700E+02 +**                                     C         +
 32  .037  .800E+02 +**                                       C       +
 36  .041  .900E+02 +**                                         C     +
 33  .038  .100E+03 +**                                           C   +
 17  .020  .110E+03 +*                                             C  +
 11  .013  .120E+03 +*                                              C +
 11  .013  .130E+03 +*                                              C +
  6  .007  .140E+03 +                                                C+
  5  .006  .150E+03 +                                                C+
 20  .023    INF    +*                                                C
---                 +    +    +    +    +    +    +    +    +    +    +
871                 0        20        40        60        80       100
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
GDFLW OMAHA WT	.444E+02	.382E+02	.859E+00	.204E+00	.269E+03	871

HISTOGRAM NUMBER24
DISCARDED MSGS

```
OBS  RELA   UPPER
FREQ FREQ  CELL LIM 0        20        40        60        80       100
                    +    +    +    +    +    +    +    +    +    +    +

                     NO VALUES RECORDED.
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
DISCARDED MSGS			NO VALUES RECORDED			

Appendix I. *Meteor Burst Consultants*

This appendix includes the names and addresses of the meteor burst consultants who provided information for this thesis effort.

Abel, Martin W.
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McLean, VA 22102
(703) 883-5922

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MCC Corporation President
6020 South 190th Street
Kent, WA 98032
(206) 251-9411

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IBM Federal Systems Division
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Gaithersburg, MD 20878

Morgan, Edward
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Annandale, VA 22003

Niedenfuhr, Francis Ph.D.
MITRE Corporation
Washington C^3I Division
7525 Colshire Drive
(703) 883-7003

Weitzen, Jay Ph.D.
Lowell University
Electrical Engineering Department
Lowell, MA 01854

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Vita

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Assistant Professor of Electrical Engineering and Computer Science

Abstract:

Meteor burst communication (MBC) is well suited for military applications. MBC offers better security compared to other long range communication systems because of its low probability of intercept and antijamming characteristics. MBC, however, has two major drawbacks: low throughput and long message waiting time. In order for MBC to be used effectively, methods need to be developed to predict and optimize system performance. The result of this research is the design and development of a methodology to analyze MBC networks.

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A decision support system was developed that provides a simulation model for any single or multiple-link MBC network. This model runs on an IBM XT/AT compatible computer and consists of two distinct components. The first component uses engineering parameters to compute intermediate queueing characteristics used by a discrete event simulation component. The simulation component provides point estimates for throughput, message delay, and resource utilization in tabular and graphical form.

The MBC process is shown to be a M/G/1 queue with server vacations. Applicable analytical equations are presented and their limitations are discussed. Analytical equations and empirical data were both used to validate the MBC performance model.

The modeling perspective presented in this research represents a new and robust method for analyzing MBC networks. Adaptive message routing, flood routing, and priority message traffic are discussed. By separating the engineering parameters of the MBC network from the simulation code, portability, ease of use, and conceptual simplicity was achieved. This research demonstrates the successful marriage of complex communication system engineering with queueing theory and simulation models to produce a highly productive analysis tool.